AD 273 556

JKO

(93 pages)
$8.60

JOSEPH KAYE AND COMPANY, INC.
49 HAMPSHIRE STREET
CAMBRIDGE 39 MASSACHUSETTS

REPORT 33

SURVEY OF LONG LIFE SYSTEMS FOR GENERATION OF ELECTRICITY AT LOW POWER IN A MARINE ENVIRONMENT

VOLUME I

Prepared for

U. S. Navy Bureau of Ships

under

Contract No. NObs-78711
Serial No. Ser-1734C-289

Attn: Chief, Bureau of Ships
Code 350
Department of the Navy
Washington 25, D. C.

August 31, 1960

JOSEPH KAYE AND COMPANY, INC.
49 Hampshire Street
Cambridge 39, Massachusetts

UNCLASSIFIED

SUMMARY

~~This report presents the results of a survey, by Joseph Kaye and Company for the U. S. Navy Bureau of Ships~~ A survey of the more, of ~~a considerable number of~~ long life systems for producing small quantities of electrical power for use in an oceanic environment. ~~The report is presented in two volumes~~.

~~Volume I contains~~ A description is given of the power-system requirements, and ~~a general discussion of~~ useful sources of energy for systems producing 2 watts for 2 years and 5 watts for 2 years are discussed. ~~The next portion of Volume I contains~~ Included is a description of energy-conversion methods, a discussion of the use of the system concept in considering the power systems, and the presentation and illustration of an energy-conversion matrix. ~~The remaining portion of Volume I presents~~ a basis for selection of attractive power systems is presented, followed by the detailed analyses of the ~~six~~ most attractive systems. The power-conversion systems ~~which are~~ considered are comprised of an energy source such as fuel and oxidant, ~~the~~ energy-conversion devices, ~~the~~ necessary control system, ~~the~~ storage tanks for the energy source, and the container to house and protect the system. Finally, the characteristics, such as weight, volume and cost of these systems are compared.

Volume II of the report presents the analyses of all remaining energy-conversion systems which were surveyed, but which were not considered to be attractive at this time. In addition, the important characteristics of all systems are compared and discussed in the same manner as in Volume I.

CONCLUSIONS AND RECOMMENDATIONS

Joseph Kaye and Company concludes that the need within five years for operational 2 watt-2 year and 5 watt-2 year power systems in mass produced quantities requires that immediate consideration be limited to power systems based upon existing and proven technology. It is further concluded that the size, cost, and efficiency of system components, such as energy sources and conversion devices, cannot be used to deduce overall system characteristics when considered outside the overall system context. The power systems can be compared and selected for development only on the basis of complete system characteristics.

On the basis of the system studies which have been made, Joseph Kaye and Company recommends the following:

1. The following power systems should be developed in parallel into hardware form:

Hydrogen-Oxygen Fuel Cell System
LeClanche Cell Battery System
Lead-Acid Battery System
Propane-Oxygen Thermoelectric System
Liquefied Gas Expansion System
Propane-Oxygen Internal Combustion Engine System

Parallel development of the above systems will assure the Navy of at least one proven power system. From several systems developed to the hardware stage, final selection of the most attractive power system or systems can be made on the basis of logistics.

2. Potentially attractive systems dependent upon further research and technical development should be pursued to make them available as future replacements. Several such systems are discussed and analyzed in Volume II of this report.

TABLE OF CONTENTS - VOLUME I

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Objective

Joseph Kaye and Company proposed to the U. S. Navy, Bureau of Ships, to survey and analyze a number of possible systems to produce electrical power continuously at the rates of 2 watts or 5 watts for 2 years when employed in an unattended oceanic environment. As a result of the proposal, contract No. NObs-78711 was initiated for an analysis and comparison of the systems described below:

a. Batteries: Lead acid, Leclanche, etc.

b. Galvanic: Magnesium-sea water, etc.

c. Mechanical: Sea wave action, etc., utilizing kinetic and/or potential energy.

d. Thermomechanical: Working fluids, etc.

e. Direct Conversion: Thermionic, thermoelectric, magnetrohydrodynamic, thermogalvanic, etc.

f. Fuel Cells

g. Solid State: Piezoelectric, pyroelectric, ferroelectric, etc.

h. Biological

i. Terrestrial: Gravity, etc.

j. Solar

Within the broad interpretation of the contract requirements, it is the objective of this survey to examine power systems based upon the several physical and chemical phenomena which are capable of meeting the electrical requirements of the needed power sources.

Statement of Problem

A need has arisen for inexpensive and reliable sources of small quantities of electrical power. These power sources will be installed in the oceans and, once in place, must operate continuously for a period of at least two years. It is also required that neither maintenance nor refueling will be necessary during this period. The modes of operation of power producing systems in a marine environment can be variously interpreted, for example:

Floating and drifting on the surface of the ocean.

Floating, but anchored to prevent drifting.

Submerged and drifting.

Submerged and anchored.

Resting on the ocean floor.

Resting on the shore.

Resting on an ice floe.

Floating in the air (low altitude balloon).

The power systems covered in this survey are devices which may operate floating and anchored, submerged and anchored, resting on the ocean floor, or floating in the air. In addition, systems will be required for use in the oceans at various latitudes, from tropical to polar. This requirement may mean that several quite different systems will be needed, each suitable for a specific local climatic condition.

Evaluation of Power Systems

Since 1945 various surveys have been made to determine the suitability of various systems to produce power for unusual applications (1, 2, 3, and 4)*.

---

*Numbers in parentheses refer to items in Bibliography.

These surveys have been oriented toward navigational beacons, high-altitude meteorological balloons, space vehicles, and similar applications. One of the primary requirements for such power systems has been compactness (size and weight), while cost has been of secondary importance. In this survey, however, it is anticipated that the power systems considered will be used in large numbers; hence cost and logistic problems assume major importance.

Evaluation of power systems has been made on the basis of broad use of the following important criteria:

Soundness of principle

Producibility, including cost and use of critical materials

Development time

Reliability

Soundness of principle is used here to denote not merely theoretical possibility, but also useful applicability to the job to be done. As an example, ion propulsion is a sound principle when applied in distant space; But it is only a ridiculous theoretical possibility when applied to a one-million-pound booster rocket.

Producibility is used to indicate the probability that a system can eventually be mass produced at reasonable cost and without excessive use of critical materials.

Development time signifies the time required to produce the final design of a proven mass producible system. In general, development time for a system will be strongly influenced by the state of the art existing at the time of selection of the various devices, concepts, techniques and materials that the system incorporates.

Reliability is the term used to indicate the degree of assurance that a power system will be able to deliver the necessary electrical power continuously, without failure, throughout the required time interval. Attempts to assess the reliability of a system requires objective judgment of a number of factors. Unfortunately, there is a tendency to consider reliability as simply an inverse function of complexity, with increasing complication automatically implying declining dependability. Indiscriminate use of such reasoning is quite dangerous in system evaluation, since a complex system made of highly reliable components may well prove more dependable than a simple system composed of a single weak component. Failure to appreciate this fact often manifests itself in the popular, but sometimes ill-founded, generalization of the virtue of "no moving parts". A comparison of the reliability of even a cheap watch with that of a ball-point pen is illustrative of the fallibility of such a generalization.

Systems and Concepts Considered

The power system survey covered by this report has included the analysis of a number of complete systems. In addition, the feasibility of many energy sources and energy conversion concepts have been examined.

Following is a list, using the categories mentioned in the contract, of the types of systems or concepts explored in this survey. Note that systems and concepts which could logically be listed in more than one category have been listed once each.

Batteries or Galvanic Devices

- Lead-acid battery
- LeClanche cell battery
- Magnesium-sea water battery
- Zinc-silver oxide battery
- Zinc-nickel oxide battery
- Zinc-mercuric oxide battery

- Nickel-cadmium battery
- Nickel-iron battery
- Lelande cell battery
- Alkaline dry cell battery
- Le Carbone cell battery
- Air cell battery
- Ion permeable membrane battery
- Charge collection nuclear battery

Mechanical

- Mechanical oscillator actuated by sea waves
- Pressure-actuated wave energy converter
- Hole-in-the-ocean system
- Spring motor energy storage
- Electrostatic generator

Thermomechanical

- Liquid ammonia energy converter
  - Closed system
  - Open system
- Liquid CO_2 energy converter
  - Closed system
  - Open system
- Compressed hydrogen energy converter
- Cartesian diver
- Propane-oxygen engine generator
- Propane-air engine generator
- Evaporation-cooled heat engine

Direct Conversion

- Propane-oxygen thermoelectric converter
- Propane-hydrogen peroxide thermoelectric converter
- Propane-air thermoelectric converter
- Lithium-water thermoelectric converter
- Sodium-water thermoelectric converter
- Hydrogen peroxide thermoelectric converter
- Oceanic thermal gradient thermoelectric converter

Polonium 210 nuclear thermoelectric converter
Cerium 144 nuclear thermoelectric converter
Strontium 90 nuclear thermoelectric converter
Mixed fission products thermoelectric converter
Propane-oxygen thermionic converter
Propane-air thermionic converter
Propane-air thermionic-thermoelectric converter
Non-isothermal electrolytic cell
Workman-Reynolds energy converter

Fuel Cells

Hydrogen-oxygen fuel cell
Redox fuel cell
Sodium amalgam-oxygen fuel cell
Hydrogen-iodine regenerative fuel cell
Bismuth-iodine regenerative fuel cell
Lithium hydride regenerative fuel cell

Solid State

Gadolinium thermomagnetic generator
Piezoelectric generator
Pyroelectric generator

Terrestrial

Falling weight
Rising underwater balloon
Rising aerial balloon
Windmill
Magnetohydrodynamic generator using ocean currents
Magnetohydrodynamic generator using ocean winds

Solar

Silicon photovoltaic generator
Cadmium sulfide photovoltaic generator
Thermionic or thermoelectric generator with focusing
Thermoelectric generator without focusing
Mercuric bromide thermogenerative fuel cell

Cadmium-iodine thermoregenerative fuel cell
Photochemically regenerative fuel cell
Silver-halide photogalvanic battery
Cuprous-cupric oxide photogalvanic cell
Electrolysis regenerated hydrogen-oxygen fuel cell
Photochemical production of H_2 by Hill reaction

Organization of Report

The results of the study of power systems are presented in this report which is designated as Report 33 of Joseph Kaye and Company. The report is separated into two volumes. Volume I contains a discussion of the survey in general, including sections on energy sources, energy conversion, and the assumptions which are applicable to all or many of the systems. The analyses and comparisons of six selected power systems are also presented in Volume I. Volume II contains the analyses and discussion of other systems or concepts considered in the survey.

ENERGY SOURCES

Power generating systems are energy-conversion devices which take energy from some source and convert it to a preferred form. For this study, direct current electricity is to be delivered by such systems. The power systems surveyed may use the terrestrial environment in which they operate as a source of energy, or they may derive energy from materials which they contain.

Environmental Energy Sources

Power generating systems can draw energy from their surroundings by use of such effects as:

- Ocean waves
- Ocean currents
- Ocean winds
- Gravity
- Thermal gradients
- Concentration gradients
- Solar radiation
- Enthalpy of the (infinite) ocean
- Volcanic activity, etc.

Systems utilizing such energy sources are composed solely of the necessary energy-conversion devices, controls, and the enclosure necessary for protection from the sea.

Stored Energy Sources

Many of the power generating systems studied herein are of the type which carry an energy source with them. These energy sources may supply the needs of the system with energy from the following effects:

Mechanical storage (spring motors, flywheels, etc.)

Thermal storage (phase changes, as fusion, sublimation, evaporation, etc.)

Chemical reactions (combustion, galvanic cells, decomposition, etc.)

Nuclear change

Power systems using stored energy consist of a reservoir of the energy storage medium, the necessary energy-conversion device or series of devices, controls, and the protective enclosure.

ENERGY CONVERSION

Conversion Processes

All power generating systems involve processes for conversion of energy from some source form to a preferred form. The conversion process may involve a broad and relatively spectacular change, using a number of conversion steps, as in the generation of electricity by the burning of coal with air; or the process may be more subtle and use only a single step, as in the conversion of alternating current electricity to direct current electricity by a solid state rectifier.

The power generating systems surveyed for this report vary greatly in the number and types of conversion steps they employ. Figure 1, reproduced from (3), is a convenient energy conversion matrix which is useful in describing briefly the conversion steps involved in a power generating system. For example, a typical fuel-air burning steam power plant can be described, using the matrix of Fig. 1, as operating according to the form,

29 a ⟶ 33 b ⟶ 19 b ⟶ 45 a

(Combustion) ⟶ (Boiler) ⟶ (Turbine) ⟶ (Generator)

An alternate example might be the generation of electricity by the combustion of fuel and air in a thermoelectric generator. This system might operate according to the form,

29 a ⟶ 47 a

(Combustion) ⟶ (Thermopile)

System Concept

First reactions to the energy conversion examples given in the preceding paragraph are likely to be that the thermoelectric generator is

FROM / TO	POTENTIAL		KINETIC — DIRECTED		KINETIC — RANDOM	ELECTRO-MAGNETIC	
	CHEMICAL	NUCLEAR	MECHANICAL	FREE PARTICLE	THERMAL	ELECTRO-MAGNETIC FIELDS	ELECTRO-MAGNETIC CIRCUITS
CHEMICAL	a) Exothermic and endothermic reactions, catalysis, etc. 1	a) Production of new elements by fission, fusion or radioactivity. 2	a) Mechanical activation of chemical processes (e.g., solion) 3	a) Radiolysis (Radiative dissociation) 4	a) Endothermic reactions b) Thermal dissociation 5	a) Photosynthesis b) Photochemistry c) Photogalvanic 6	a) Electrolysis b) Arc Dissociation c) Association 7
NUCLEAR	8	a) Fission b) Fusion c) Radioactive isotopes d) Photodisintegration e) Nuclear bombardment 9	10	a) Fission b) Spallation c) Fusion d) Nuclear bombardment 11	a) Fusion processes b) Fission processes 12	a) Photodisintegration (γ-n, γ-p, γ-d, γ-t) 13	14
MECHANICAL	a) Equilibrium volume and pressure processes 15	16	a) Compressors b) Compressed gas engines c) Mechanical couplings and gear trains d) Mass accelerators (propellors, etc.) 17	a) Ion propulsion b) Radiation sail 18	a) Positive displacement engines b) Turbines c) Thermal expansion of liquids and solids 19	a) Radiation turbine b) Radiation sail c) Electro-magnetic field reactions on conductors 20	a) Vibrators b) Solenoids c) Motors d) Accelerators e) Magnetostriction 21
FREE PARTICLE	22	a) Radioactive emission b) Photodisintegration c) Nuclear bombardment 23	a) Mechanical spark generators 24	a) Secondary emission b) Fusion processes 25	a) Evaporation b) Thermionic emission c) Fusion processes d) Fission processes 26	a) Photoemission b) Volume photoelectric effect in gases c) Compton effect d) Exciton formation in insulators e) Photodisintegration 27	a) Field emission b) Accelerators 28
THERMAL	a) Combustion b) Explosion c) Other exothermic reactions d) Catalysis 29	a) Fission b) Fusion c) Radioactive isotopes 30	a) Various mechanisms classified as friction b) Heat of compression 31	a) Atomic absorption b) Recombination c) Isotope devices 32	a) Heat exchangers b) Boilers c) Refrigerators 33	Direct Absorption by Matter a) Solar collectors b) Diathermic devices 34	a) Resistive heating b) Induction heating c) Ion gas generation d) Magnetohydrodynamics 35
ELECTRO-MAGNETIC FIELDS	a) Chemiluminescence 36	a) Fission b) Fusion c) γ to radio d) Photonuclear reactions 37	a) Triboluminescence 38	a) Cosmic radiation b) Bremsstrahlung c) Cathode luminescence d) Fusion e) Nuclear bombardment 39	a) Black body emission b) Grey body emission c) Spectrally selective emission d) Thermoluminescence 40	a) Rayleigh scattering b) Raman scattering c) Resonance fluorescence d) Photoluminescence e) Stokes and anti-stokes fluorescence f) Optical systems g) Polarization h) Frequency transformers 41	a) Electromagnetic radiation, transmitters, antenna b) X-rays c) Light (fluorescence) d) Klystron, magnetron e) Electroluminescence 42
ELECTRO-MAGNETIC CIRCUITS	a) Fuel cell b) Battery c) Ion permeable membranes 43	a) Radioisotope electrostatic generators b) Fusion 44	a) Generators b) Accelerators c) Electrostatic devices d) Piezo-electric devices e) Magnetostriction 45	a) Thermal (isotope) batteries b) Electron voltaic effect c) Secondary emission 46	a) Thermopiles b) Thermionic emission devices c) Workman-Reynolds effect d) Thermomagnetics e) Pyro-electricity 47	a) Photoelectric devices b) Photogalvanic devices c) Antennae d) Interaction between fields and conductors 48	a) Inverters b) Transformers, solenoids magnetic circuits c) Rectifiers 49

FIG. 1 **ENERGY CONVERSION MATRIX**

Reproduced from Fig. 2, page 19, of reference 3

	POTENTIAL		KINETIC			ELECTRO-MAGNETIC	
			DIRECTED		RANDOM		
TO \ FROM	CHEMICAL	NUCLEAR	MECHANICAL	FREE PARTICLE	THERMAL	ELECTRO-MAGNETIC FIELDS	ELECTRO-MAGNETIC CIRCUITS
CHEMICAL	a) Exothermic and endothermic reactions, catalysis, etc. 1	a) Production of new elements by fission, fusion or radioactivity. 2	a) Mechanical activation of chemical processes (e.g., solion) 3	a) Radiolysis (Radiative dissociation) 4	a) Endothermic reactions b) Thermal dissociation 5	a) Photosynthesis b) Photochemistry c) Photogalvanic 6	a) Electrolysis b) Arc Dissociation c) Association 7
NUCLEAR	8	a) Fission b) Fusion c) Radioactive isotopes d) Photodisintegration e) Nuclear bombardment 9	10	a) Fission b) Spallation c) Fusion d) Nuclear bombardment 11	a) Fusion processes b) Fission processes 12	a) Photodisintegration (γ-n, γ-p, γ-d, γ-t) 13	14
MECHANICAL	a) Equilibrium volume and pressure processes 15	16	a) Compressors b) Compressed gas engines c) Mechanical couplings and gear trains d) Mass accelerators (propellors, etc.) 17	a) Ion propulsion b) Radiation sail 18	a) Positive displacement engines b) Turbines c) Thermal expansion of liquids and solids 19	a) Radiation turbine b) Radiation sail c) Electro-magnetic field reactions on conductors 20	a) Vibrators b) Solenoids c) Motors d) Accelerators e) Magnetostriction 21
FREE PARTICLE	22	a) Radioactive emission b) Photodisintegration c) Nuclear bombardment 23	a) Mechanical spark generators 24	a) Secondary emission b) Fusion processes 25	a) Evaporation b) Thermionic emission c) Fusion processes d) Fission processes 26	a) Photoemission b) Volume photoelectric effect in gases c) Compton effect d) Exciton formation in insulators e) Photodisintegration 27	a) Field emission b) Accelerators 28
THERMAL	a) Combustion b) Explosion c) Other exothermic reactions d) Catalysis 29	a) Fission b) Fusion c) Radioactive isotopes 30	a) Various mechanisms classified as friction b) Heat of compression 31	a) Atomic absorption b) Recombination c) Isotope devices 32	a) Heat exchangers b) Boilers c) Refrigerators 33	Direct Absorption by Matter a) Solar collectors b) Diathermic devices 34	a) Resistive heating b) Induction heating c) Ion gas generation d) Magnetohydrodynamics 35
ELECTRO-MAGNETIC FIELDS	a) Chemiluminescence 36	a) Fission b) Fusion c) γ to radio d) Photonuclear reactions 37	a) Triboluminescence 38	a) Cosmic radiation b) Bremsstrahlung c) Cathode luminescence d) Fusion e) Nuclear bombardment 39	a) Black body emission b) Grey body emission c) Spectrally selective emission d) Thermoluminescence 40	a) Rayleigh scattering b) Raman scattering c) Resonance fluorescence d) Photoluminescence e) Stokes and anti-stokes fluorescence f) Optical systems g) Polarization h) Frequency transformers 41	a) Electromagnetic radiation, transmitters, antenna b) X-rays c) Light (fluorescence) d) Klystron, magnetron e) Electroluminescence 42
ELECTRO-MAGNETIC CIRCUITS	a) Fuel cell b) Battery c) Ion permeable membrances 43	a) Radioisotope electrostatic generators b) Fusion 44	a) Generators b) Accelerators c) Electrostatic devices d) Piezo-electric devices e) Magnetostriction 45	a) Thermal (isotope) batteries b) Electron voltaic effect c) Secondary emission 46	a) Thermopiles b) Thermionic emission devices c) Workman-Reynolds effect d) Thermomagnetics e) Pyro-electricity 47	a) Photoelectric devices b) Photogalvanic devices c) Antennae d) Interaction between fields and conductors 48	a) Inverters b) Transformers, solenoide magnetic circuits c) Rectifiers 49

FIG. 1 ENERGY CONVERSION MATRIX

Reproduced from Fig. 2, page 19, of reference 3 capable of converting the chemical energy available in fuel and air directly to electricity by a process involving fewer steps than are required in the usual steam power plant. However, let us now raise this question: is this simple comparison valid as a criterion in judging the relative merits of these two processes when considering them for one specific application? Some simple examples will show that the comparison is not valid until the processes have been refined or elaborated as necessary to convert them to systems able to supply power in its preferred form for a specific end use.

Let us again consider the steam and thermoelectric power generators with the specification that their outputs be suitable for connection into the usual commercial electrical power networks. It is well known that in the United States the output of the steam generating station's alternator is three-phase alternating current electricity at a moderately high voltage suitable for transmission and distribution networks. On the other hand, the thermoelectric generator produces low voltage direct current electricity which cannot be fed into the transmission networks until the additional steps of conversion to polyphase alternating current, and transformation to a high voltage have been accomplished. Using the energy conversion matrix notation, the two comparable systems now operate as follows:

steam generating plant operates

$$29\,a \longrightarrow 33\,b \longrightarrow 19\,b \longrightarrow 45\,a$$

(Combustion) → (Boiler) → (Turbine) → (Generator)

while the thermoelectric plant revised to deliver high voltage alternating current now operates

$$29\,a \longrightarrow 47\,a \longrightarrow 49\,a \longrightarrow 49\,b$$

(Combustion) → (Thermopile) → (Inverter) → (Transformer)

The requirement that both processes become systems applicable to the same end use has introduced a penalty of two additional conversion steps to the thermoelectric system, increased its weight, volume and complexity, and raised a serious question as to its suitability to the particular application.

On the other hand, changing the application to one of generation of low voltage direct current electricity for use in an electroplating plant would allow the thermoelectric generator to continue to operate

29 a ⟶ 47 a

(Combustion) ⟶ (Thermopile)

while the steam power plant would require the addition of transformers and rectifiers, or a motor generator set, to change it to the desired system whose output is low voltage DC. The steam power system would then operate

29 a ⟶ 33 b ⟶ 19 b ⟶ 45 a ⟶ 49 b ⟶ 49 c

Combustion ⟶ Boiler ⟶ Turbine ⟶ Generator ⟶ Transformer ⟶ Rectifier

or

29 a ⟶ 33 b ⟶ 19 b ⟶ 45 a ⟶ 21 c ⟶ 45 a

Combustion ⟶ Boiler ⟶ Turbine ⟶ Generator ⟶ Motor ⟶ Generator

With this set of end use specifications, the thermoelectric system retains its original simplicity while additional complications have been introduced into the steam power plant.

These examples illustrate our belief that the proper evaluation of any energy conversion scheme must be based on analysis of a complete system consistent with the following ground rules:

1. The system must contain all elements necessary to permit it to supply output power at the conditions required for the end use.

2. The system components, and supply of energy source material, must be adequate to deliver the required output power for the period of time necessary.

3. The system must include the necessary protective enclosure and structural elements to allow it to survive in the environment of its end use.

ASSUMPTIONS USED IN SYSTEM ANALYSES

General Assumptions

In order to make meaningful analyses and comparisons of various power generating systems, it is necessary, as far as practical, that all parts of these systems be designed in accordance with a common set of basic specifications. Some of these specifications are determined by the application; other specifications are not so determined, and in these cases the specifications must be assumed. Where such assumptions are required, they are based upon best present day state of the art, as determined by consultation with manufacturers and development groups active in the particular fields.

Unless otherwise stated within individual system analyses, all systems are based upon the following:

1. System net power output is 2 watts, or 5 watts.

2. System design life is 2 years of continuous output, without servicing or attention of any nature.

3. System output is 28 volts D.C. with a tolerance of plus or minus 10 per cent. Thus battery powered systems may start at 30.8 V.D.C. and be considered at the end of their lives at 25.2 V.D.C.

4. All systems are designed to generate electricity within the range of 1.5 volts minimum to 440 volts maximum. An auxiliary solid state device will be added to the system when necessary to change the generated output to 28 volts D.C.

5. All closed systems are designed to be hermetically sealed: i.e., the only opening in the container is for passage of the electrical output leads. The selected systems presented in Volume I of this report operate as closed systems.

6. All open systems operate with internal pressure higher than the ambient sea pressure, or are designed in such manner as to allow only the outward venting of exhaust products from the power generator, or are designed to allow a controlled inlet of sea water if it is required by the generating system.

7. Systems may be designed for operation on the ocean surface, resting in or upon the ocean bottom at a depth of 5000 feet, or at stable or varying intermediate depths. Unless otherwise stated in the analysis for a particular system, the power systems are assumed to operate moored at a depth of 200 feet.

8. Mechanically driven electric generators, except special types such as piezoelectric devices, have an overall mechanical to electrical conversion efficiency of 50 per cent.

9. Storage batteries used in intermittent systems, where they are periodically discharged and recharged, provide a 75 per cent charge to discharge efficiency, assuming a normal maximum discharge of 50 per cent of capacity on each cycle.

10. All systems using gear trains are designed on the basis of weight, volume, and cost as determined from Figs. 2 through 4, respectively, for the particular ratio and load required. Gear-train efficiency is based on Table 1.

11. Systems are housed in containers made from low carbon steel, or low alloy steel, with a coating such as vinyl plastic for prevention of corrosion by the sea water. All containers and pressure vessels are designed in accordance with the section entitled, "Containers and Pressure Vessels".

12. Ballast weights are made from concrete at a fabricated cost of $12.50 per cubic yard ($6.20 per ton). Density of the concrete is 150 lb/cu ft. and its effective negative buoyancy is 86 lb/cu ft.

Speed Reducers Or Increasers

For sizing geared speed reducers or increasers, graphs of size, weight, and cost as a function of the maximum torque and speed ratio have been prepared based on information from Boston Gear Catalogue Number 56, 1956. These figures are given for worm and spur gear types. The values used to estimate weights, volumes, and costs of gear trains are contained in Figs, 2, 3, and 4, respectively.

For a particular gear train, variations in speed have only a small effect on the maximum permissible torque in the system, providing high centrifugal stresses are not reached. Hence, effects of gear speed have been neglected. Where high speed ratios are desirable, a device such as the harmonic drive developed by United Shoe Machinery Corporation may prove to be advantageous in obtaining small size, low weight, and high efficiency. However, in this survey, the figures used in estimating weight, volume, and cost are based on conventional spur and worm gear designs.

A table of gear efficiency versus speed ratio has been prepared based on information taken from (5). This information is summarized in Table 1.

Table 1
EFFICIENCY VS. SPEED RATIO OF GEAR TRAINS

Speed Ratio	Efficiency (per cent)
10/1	98.00
100/1	96.04
1,000/1	94.12
10,000/1	92.24
100,000/1	90.40
1,000,000/1	88.60

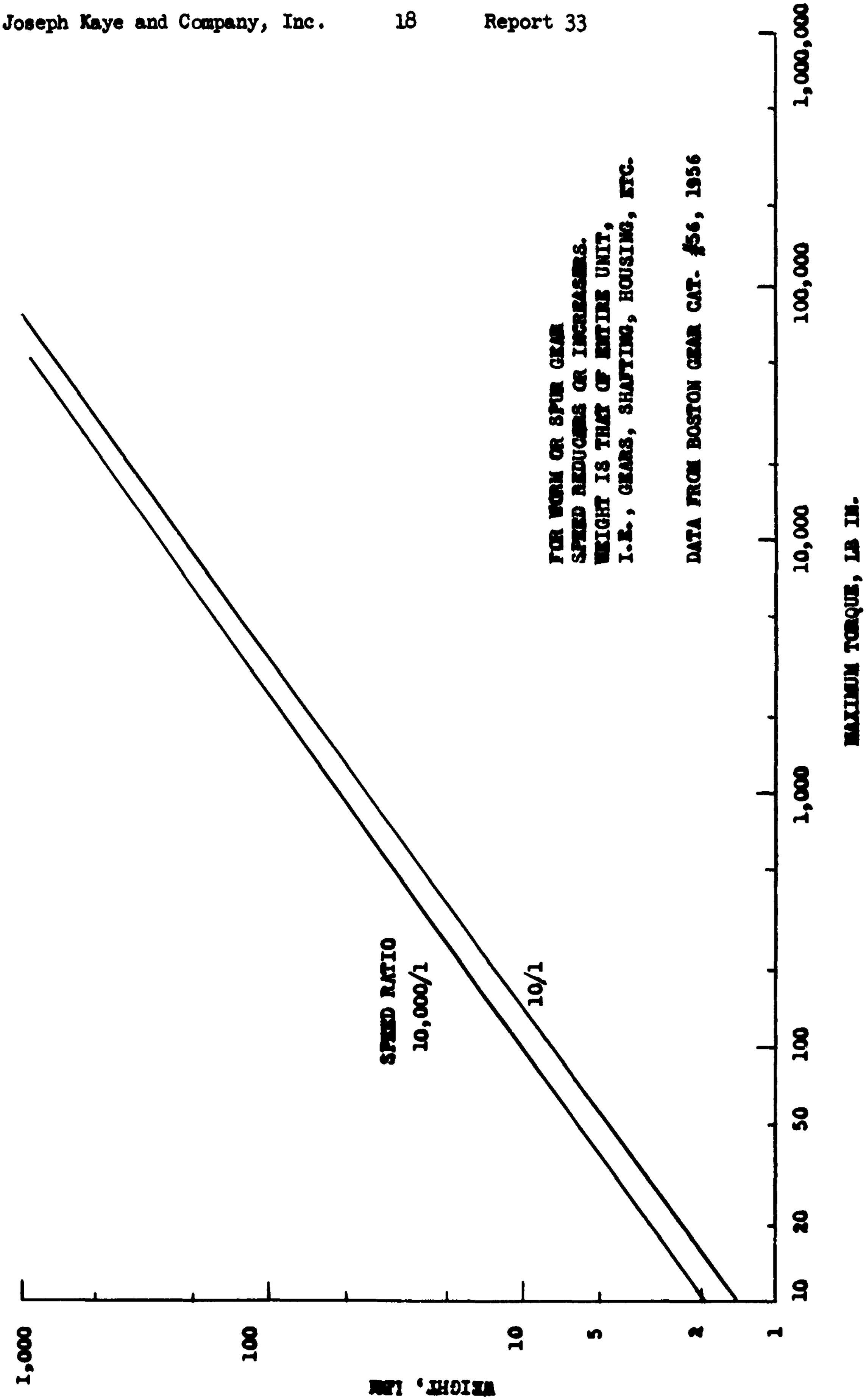

FIG. 2 WEIGHT VERSUS MAXIMUM TORQUE FOR SPEED INCREASERS AND REDUCERS

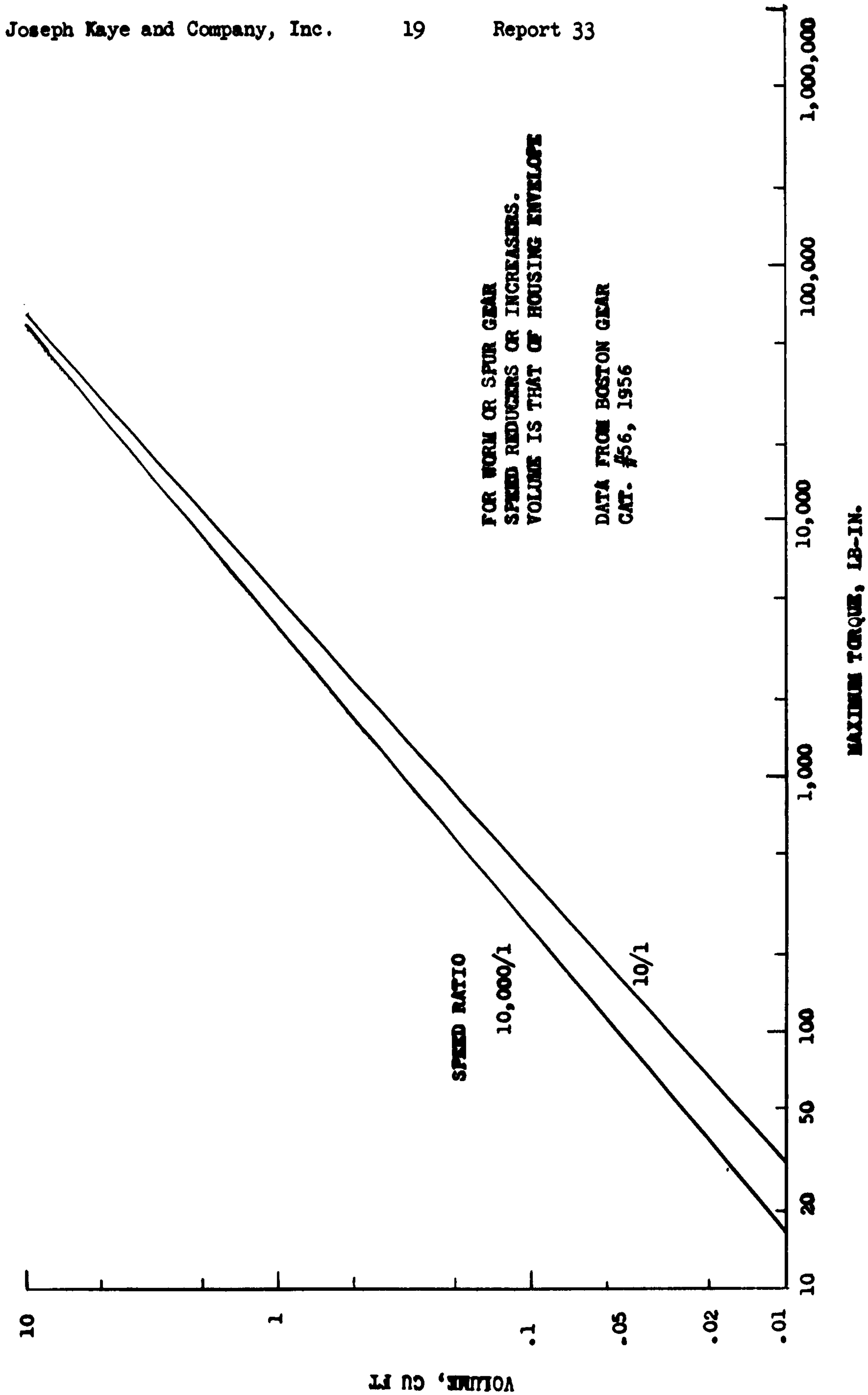

FIG. 3 VOLUME VERSUS MAXIMUM TORQUE FOR SPEED INCREASERS AND REDUCERS

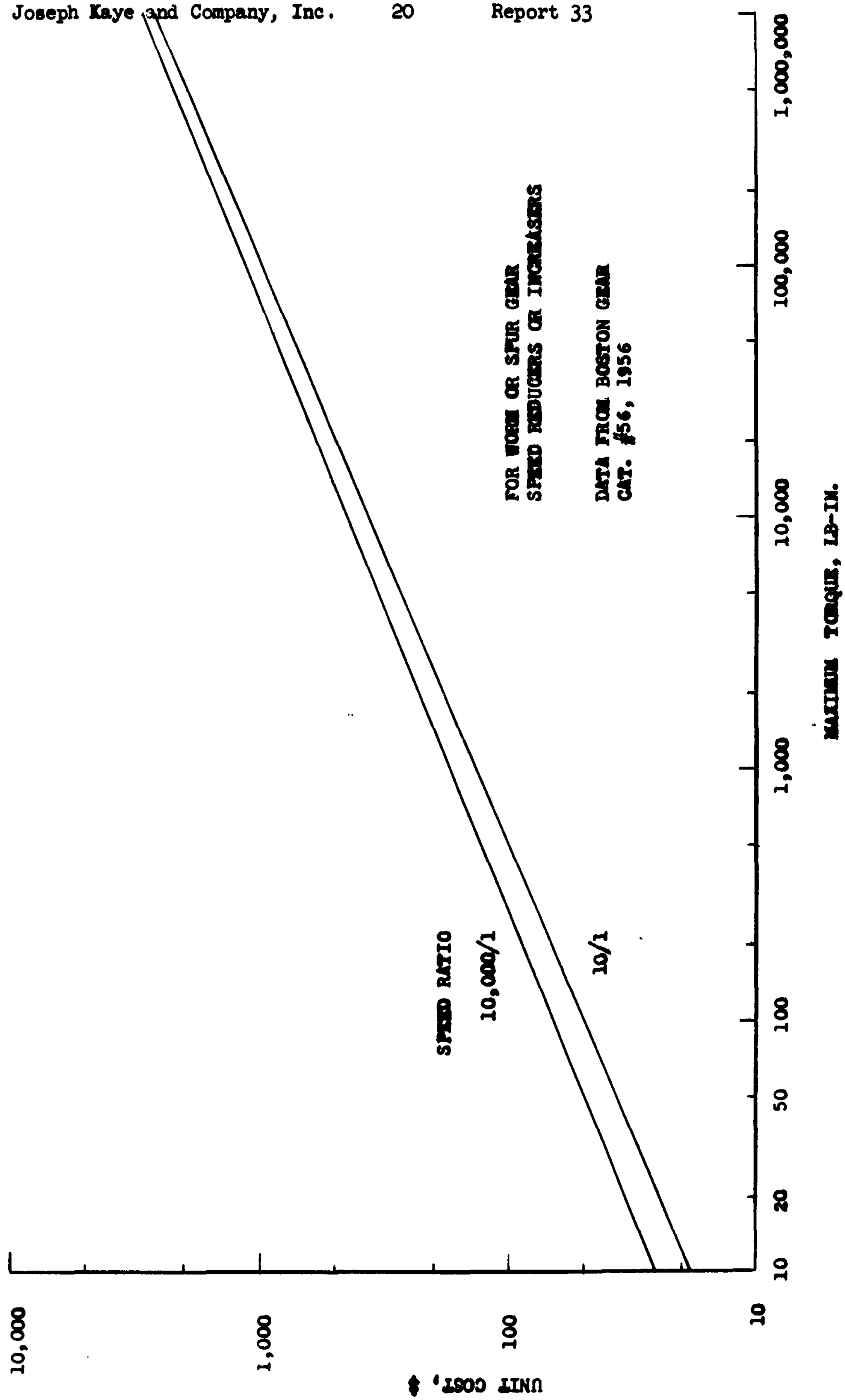

FIG. 4 COST VERSUS MAXIMUM TORQUE FOR SPEED INCREASERS AND REDUCERS

Containers and Pressure Vessels

This section presents the criteria for estimating dimensions, weights, and costs of containers for enclosing the energy-conversion systems and of pressure vessels for storage of energy-source materials. To permit comparison of the parameters of the systems, the assumptions used in making estimates of these parameters have been made on bases which are common and which appear reasonable though not optimum, for all systems. There are three general categories of container and pressure vessels which are listed and described briefly as follows:

1. Containers

A container is the protective shell which encloses all or a portion of a power system. Although a container is not conceived primarily to be a pressure vessel, as might be used for storage of an energy-source material, it must sustain the worst pressure loading which may occur at depths from sea level to 200 ft. The worst pressure loading is defined as that loading which will result exactly in reaching one of the several buckling or maximum stress criteria. The shape of containers will be either spherical or cylindrical, depending upon the individual needs of the systems. All containers will be made of low carbon steel coated with vinyl for resisting sea water corrosion.

2. Vessels for Medium Pressures

Many systems require storage vessels capable of withstanding internal pressures of several hundred pounds per square inch. Such vessels are assumed to be made of low carbon steel, either uncoated if contained inside an enclosure, or coated with vinyl if exposed to the sea. These vessels for moderate pressures will usually have internal pressures which exceed the pressure at ocean depths from sea level to 200 ft. Thus, these vessels usually can be designed on a criterion of maximum tensile stress. In the cases where the external pressure on the vessel at a depth of 200 ft exceeds the internal pressure, the designs have been checked to assure adequate strength to prevent buckling. The shapes of vessels for moderate pressures are generally spherical, although cylindrical vessels are employed in some systems if desirable.

3. Vessels for High Pressures

Several systems require vessels to contain gases used as fuel and/or oxidant stored at high pressures, such as 6000 psi. If these high pressure vessels were constructed of low carbon steel in the fashion of containers and vessels for medium pressures, the wall thickness of high pressure vessels could be several inches in some cases. Therefore, it is assumed that the material used to fabricate high pressure vessels is an alloy steel which has a considerably higher yield point than that of the low carbon steel used for containers and vessels for medium pressures. These high pressure vessels are of spherical shape.

Design Criteria

The design criteria and property values which have been used to calculate the dimensions, weights, and costs of containers and pressure vessels are given as follows:

The material to be used for fabricating containers and vessels for medium pressures is low carbon steel. The material to be used for fabricating high pressure tanks is alloy steel. These materials would have the following properties:

Young's Modulus	=	30×10^6 psi
Poisson's Ratio	=	0.3
Density of Steel	=	485 lbm/ft^3

The design constraints on the containers and vessels for medium pressure are given as follows:

Maximum Tensile or Compressive Stress	$\leq$	15,000 psi
Minimum Wall Thickness	$\geq$	0.125 in
Ratio of Length to Diameter of Cylinders	=	5
$\frac{\text{Thickness of Walls of Cylinders}}{\text{Thickness of Heads of Cylinders}}$	=	1

The design constraint on high pressure vessels is given as follows:

Working Tensile Stress = 50,000 psi

The equations for designing for the allowable tensile and compressive stresses are:

Spheres: $\sigma_m = pr/2\,t$

Cylinders: $\sigma_m = pr/t$

where

σ_m = maximum allowable stress

Δp = magnitude of difference in pressure between interior and exterior of tank

r = radius of tank

t = thickness of tank wall

All containers and vessels for medium pressures were checked against the appropriate buckling criteria when loaded in compression. These criteria are given as follows:

Spheres: $\Delta p_c = 2E(t/r)^2/\sqrt{3(1-\mu^2)}$

Cylinders with circularly constrained ends:

$$\Delta p_c = 0.807(Et^2/\ell\, r)\sqrt[4]{(t/r)^2/(1-\mu^2)^3}$$

where

Δp_c = critical buckling pressure difference

E = Young's modulus

t = thickness of tank wall

r = radius of tank

ℓ = length of tank, if cylindrical

μ = Poisson's ratio

Each tank design was checked against the appropriate buckling criterion. The tank wall was assumed to be thick enough if the calculated value of critical pressure difference was at least twice as large as the actual pressure difference.

Based on information obtained from reliable manufacturers of steel tanks, the following system of costs was applied in estimating total costs of containers in fabricated form.

Cost of container or medium pressure vessel with wall thickness of 1/8 in., uncoated	\$0.20/lbm steel
Cost of container or medium pressure vessel with wall thickness of 1/8 in., vinyl coated	\$0.30/lbm steel
Cost of container or medium pressure vessel with wall thickness greater than 1/8 in., uncoated	\$0.50/lbm steel
Cost of container or medium pressure vessel with wall thickness greater than 1/8 in., vinyl coated	\$0.60/lbm steel
Cost of high pressure vessel, uncoated	\$0.50/lbm steel
Cost of high pressure vessel, vinyl coated	\$0.60/lbm steel

The large increase in cost of tanks which have a wall thickness greater than 1/8 in. is due to the more difficult and expensive methods required to fabricate these thicker walled tanks.

The design strength criteria of the various types of tanks were used to make design charts. Examples of these design charts are shown in Figs. 5, 6, and 7 for spherical containers and medium pressure vessels, based on a tensile strength criterion. These charts give weight and cost of uncoated and vinyl coated tanks as a function of the enclosed volume.

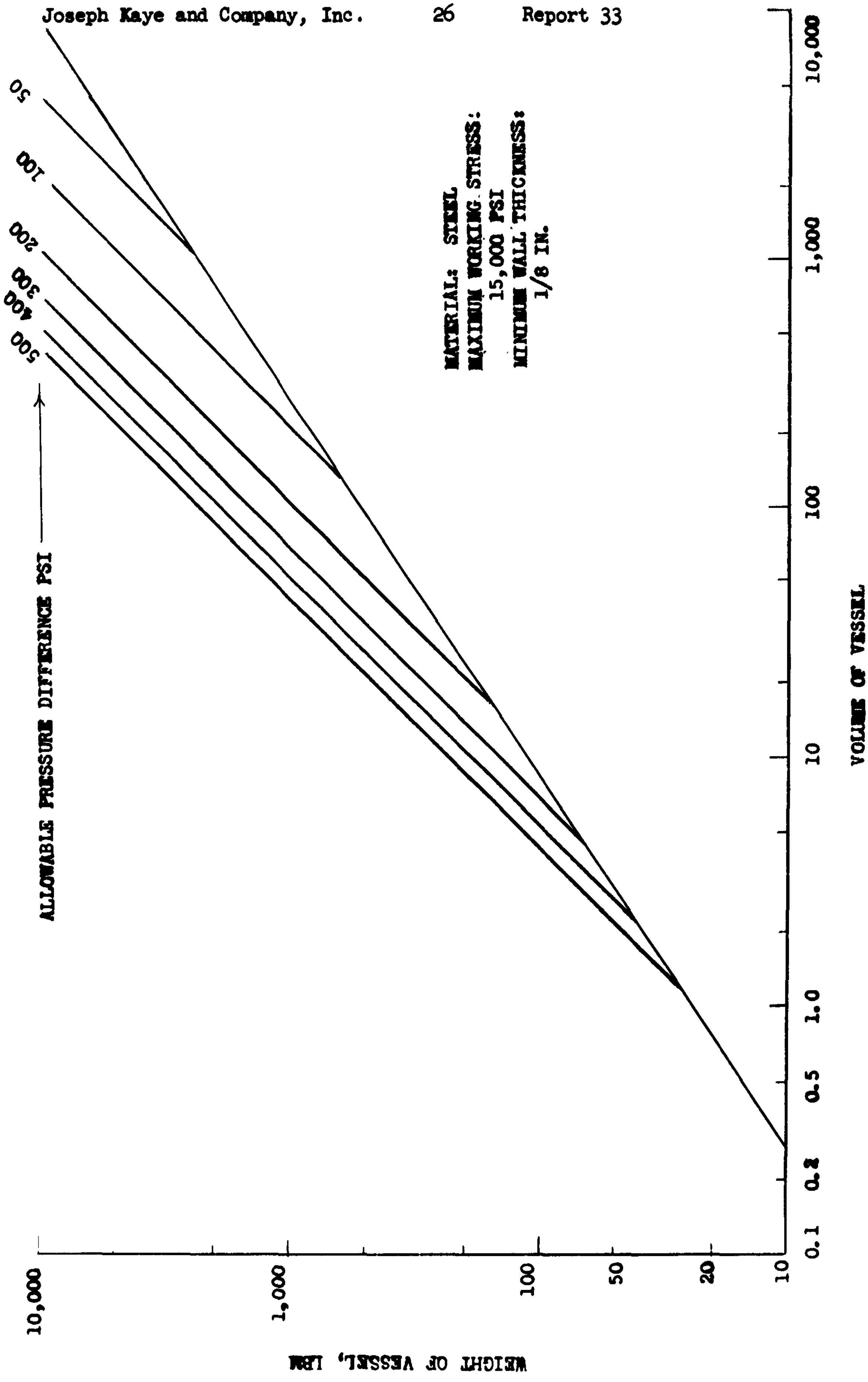

FIG. 5 WEIGHT VS. VOLUME OF SPHERICAL VESSELS FOR MEDIUM PRESSURES

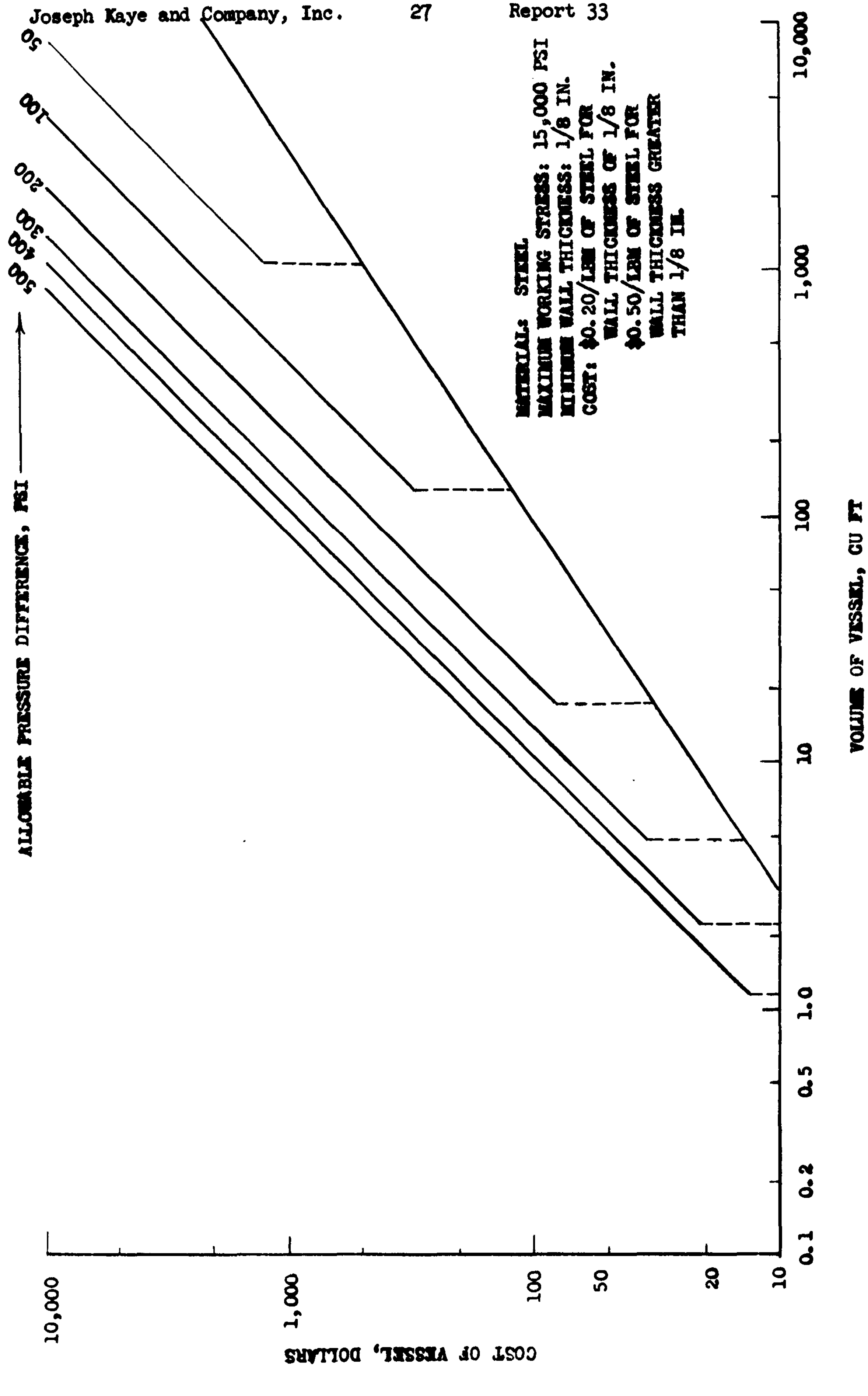

FIG. 6 COST VS. VOLUME OF UNCOATED SPHERICAL VESSELS FOR MEDIUM PRESSURES

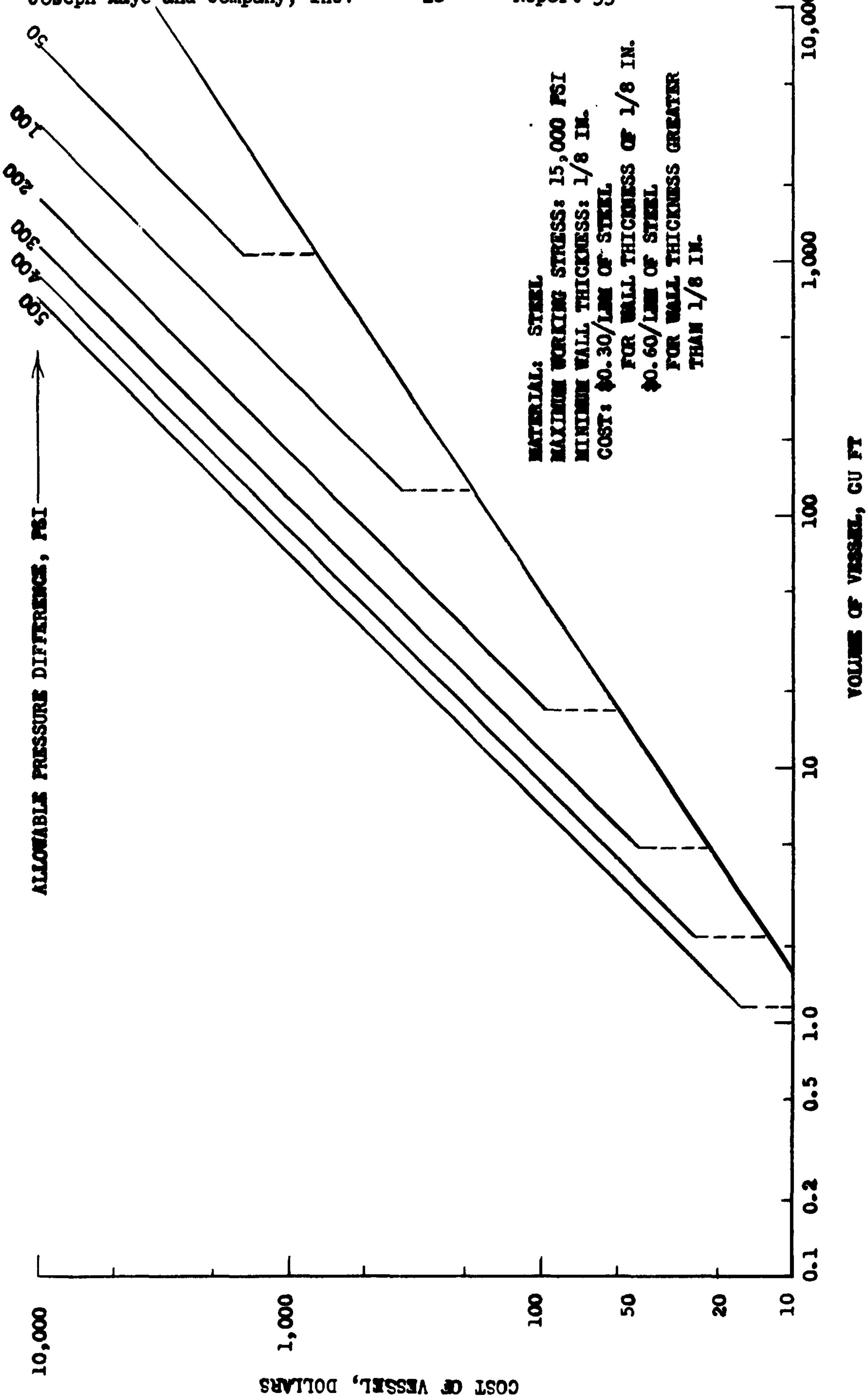

FIG. 7 COST VS. VOLUME OF VINYL-COATED SPHERICAL VESSELS FOR MEDIUM PRESSURE

COMPARISON OF SELECTED SYSTEMS

In later sections of this report, the characteristics of the six attractive power systems have been developed. To insure the validity of any comparison of the various power systems, they have been analyzed using the common group of assumptions previously described.

The important characteristics of the six selected systems are presented for comparison in Tables 2 and 3. The terms used in these comparison tables are:

SYSTEM. The system includes the energy conversion device, the fuel or energy source excluding environmental energy sources, and all enclosures such as fuel tanks, floats, and encapsulation chambers. Essentially, the system is the complete power package ready to be placed in the ocean, exclusive of anchoring devices.

SYSTEM COST. The system cost is the estimated total cost to the government of each power system when the design is in mass production.

SYSTEM WEIGHT. The system weight is the weight of the entire power system ready to be dropped into the ocean. No anchor or cable weights are included.

SYSTEM VOLUME. The system volume is equivalent to the volume of water displaced by the power system when submerged.

OPERATING DEPTH. The operating depth indicates the location of the power system relative to the surface when operating in the ocean.

CONVERSION DEVICE

a. Cost. This is the cost of the conversion device only. The cost is given per watt of power system output. In the majority of systems the cost, weight and volume of the conversion device will be largely a function of the power level of the system.

b. Weight. The weight of the conversion device is given per watt of power system output.

c. Volume. The volume of the conversion device is based upon its overall dimensions and is given per watt of power system output.

EXPENDABLES

a. Cost. The cost of the expendables in the majority of cases is the cost of the fuel and oxidant only, and is given per watt-year of power system output. Battery systems are exceptions to this rule. The container, electrodes, and electrolyte are generally packaged as a unit, hence, when parameters of battery systems are reported, the expendables include its container. In the systems which require calcium oxide for the absorption of products of combustion, the calcium oxide is considered an expendable. Environmental energy sources are considered to be free.

b. Weight. The expendables weight is given per watt-year of power system output.

c. Volume. The volume of the expendables is given per watt-year of power system output.

ENCLOSURES

a. Cost. Enclosure costs include costs of fuel tanks, compressed gas tanks, encapsulation chambers, and flotation tanks. Enclosure costs are given per watt-year of power system output.

b. Weight. The weights of the above enclosures are given per watt-year of power system output.

c. Volume. The envelope volume of the enclosures is given per watt-year of power system output.

be obtained from the organization involved in fuel-cell research before this problem can be properly evaluated.

The LeClanche cell battery system is one of the more attractive systems on the bases of cost, weight, and volume. This system is the only one of the selected systems which would require replacement of almost the entire system after 2 years time. The importance of this fact cannot be evaluated until the logistics of the entire system concept are considered. It may prove so expensive to place systems in the ocean and service them at two-year intervals that the alternatives of either recharging or replacing systems are academic.

The lead-acid battery system is one of the more expensive of the selected systems. However, this system can be recharged several times. Moreover, recharing could probably be accomplished without either opening the system container or removing the system from the ocean.

The propane-oxygen thermoelectric system is the most expensive of the selected systems and is one of the heavier and more voluminous ones as well. However, a large fraction of the system weight is attributable to the calcium oxide tank and its contents for absorbing exhaust gases. If the requirement we have imposed for a closed system were relaxed, the weight could be reduced substantially. This system also has a large negative buoyancy force, largely attributable to the calcium oxide tank. The semiconductor materials for the thermopile could become critical if consumption increases markedly for civilian and other governmental purposes.

The liquefied gas expansion system is the heaviest of the selected systems. However, the cost is reasonable, and the cost, weight, and volume could be reduced substantially by using concrete tanks and by allowing the system to exhaust directly overboard. A point in favor of the liquefied gas

ENERGY DENSITY OF EXPENDABLES. The energy density of the expendables refers to the theoretical maximum energy which could be extracted from the expendables. The term, weight per watt-year of the expendables, however, is not the inverse of the energy density, since the weight of expendables required in a power system is dependent upon the overall efficiency of the conversion system.

Table 2 presents the overall characteristics of the six selected systems when designed for an output of 2 watts for 2 years. Also presented are the characteristics of the energy sources, energy conversion devices, and the power system enclosures. Table 3 presents similar data for 5 watts, 2 years systems.

It is most important, when referring to Tables 2 and 3, and the listings of system characteristics in each system discussion, to remember that system and component characteristics presented on a per-watt or per-watt-year basis cannot generally be used for scaling purposes. Such characteristics usually are unique to the particular system and contain factors which vary in a non-linear fashion with system output. It may in fact occur that a system component does not vary in total size or cost as the system power is increased. In such a case the cost, size and weight of the component per watt or per watt-year actually diminish with increasing system output.

The hydrogen-oxygen fuel cell system appears to be the most outstanding system considered, on the bases of its low cost, low weight, and small volume. The fuel-cell system, as it is described herein, would require the addition of a small volume of flotation material or space to offset its negative buoyancy. However, since the negative buoyancy force is not large compared with the system weight, this problem can be solved fairly easily. The required catalyst poses a critical materials problem. More information will have to expansion system is that it is based on very well understood and practised principles of operation.

The propane-oxygen internal combustion engine system is one of the least expensive of the selected systems and has moderate weight and volume. This system is based on decades of practical experience and would have very good reliability if properly developed.

In several of the selected systems, large fractions of the total weights and costs are due to storage of exhaust products. If small, inexpensive devices were available for disposing of the exhaust products directly in the ocean without increasing the likelihood of detection, these systems would benefit greatly. In fact, most of the systems will derive sizable benefits in reducing their costs, weights, and volumes when each system is optimized with respect to its own variables rather than designed according to a common set of conditions.

TABLE 2

COMPARISON OF POWER SYSTEMS PRODUCING 2 WATTS FOR

CHARACTERISTICS OF COMPLETE SYS

System	System Cost $	System Weight lbm	kg
Hydrogen-Oxygen Fuel Cell	380	420	190
LeClanche Cell Battery	830	1,770	800
Lead-Acid Battery	1,680	3,350	1,520
Propane-Oxygen Thermoelectric Generator	2,400	7,100	3,200
Liquefied Gas Expansion Engine	1,050	11,700	5,300
Propane-Oxygen Internal Combustion Engine	770	2,370	1,080

CHARACTERISTICS OF SYSTEM COMPONE

	Conversion Device					Expendat		
	Cost	Weight		Volume		Cost	Weight	
	$/w	lbm/w	kg/w	cu ft/w	cu m/w	$/w-yr	lbm/w-yr	kg/w-yr
Hydrogen-Oxygen Fuel Cell	50	1.5	0.7	.03	.0008	2	6	3
LeClanche Cell Battery	180	500	230	5	0.14	N.A.	N.A.	N.A.
Lead-Acid Battery	700	1,370	630	12.4	0.36	N.A.	N.A.	N.A.
Propane-Oxygen Thermoelectric Generator	250	20	9	0.5	.01	36	1,010	460
Liquefied Gas Expansion Engine	50	5	2	0.5	.01	46	2,550	1,160
Propane-Oxygen Internal Combustion Engine	53	11	5	0.4	.01	10	290	130

BLE 2

WATTS FOR 2 YEARS AT 28 VOLTS D.C.

F COMPLETE SYSTEM

m Weight	System Volume		Operating Depth
kg	cu ft	cu m	ft
190	6	0.2	200
800	29	0.8	200
1,520	55	1.5	200
3,200	63	1.8	200
5,300	294	8.3	200
1,080	40	1.2	200

YSTEM COMPONENTS

Expendables					Enclosures			
Weight		Volume		Cost	Weight		Volume	
yr	kg/w-yr	cu ft/w-yr	cu m/w-yr	$/w-yr	lbm/w-yr	kg/w-yr	cu ft/w-yr	cu m/w-yr
	3	0.5	.01	55	97	44	2	.06
.	N.A.	N.A.	N.A.	26	88	40	7	.20
.	N.A.	N.A.	N.A.	39	130	59	14	.40
	460	15.5	.40	430	760	350	15.5	.44
	1,160	74	2.1	180	370	168	73	2.1
	130	5	.14	130	290	132	13	.37

TABLE 3

COMPARISON OF POWER SYSTEMS PRODUCING 5 WATTS

CHARACTERISTICS OF COMPLE

System	System Cost $	System Weight lbm	kg
Hydrogen-Oxygen Fuel Cell	660	1,040	470
LeClanche Cell Battery	1,920	4,300	1,960
Lead-Acid Battery	4,100	8,300	3,760
Propane-Oxygen Thermoelectric Generator	5,200	17,600	8,000
Liquefied Gas Expansion Engine	2,740	29,200	13,200
Propane-Oxygen Internal Combustion Engine	1,575	5,750	2,610

CHARACTERISTICS OF SYSTEM C

	Conversion Device					Ex		
	Cost $/w	Weight lbm/w	kg/w	Volume cu ft/w	cu m/w	Cost $/w-yr	Weight lbm/w-yr	kg/
Hydrogen-Oxygen Fuel Cell	20	1.5	0.7	.03	.0008	2	6	
LeClanche Cell Battery	180	500	230	5	0.14	N.A.	N.A.	N.
Lead-Acid Battery	680	1,350	610	12.2	0.34	N.A.	N.A.	N.
Propane-Oxygen Thermoelectric Generator	100	8	4	0.2	.006	36	1,010	46
Liquefied Gas Expansion Engine	20	2	1	0.2	.006	46	2,550	1,16
Propane-Oxygen Internal Combustion Engine	26	7	3	0.1	.003	10	290	13

BLE 3

5 WATTS FOR 2 YEARS AT 28 VOLTS D.C.

OF COMPLETE SYSTEM

em Weight		System Volume		Operating Depth
	kg	cu ft	cu m	ft
)	470	15	0.4	200
)	1,960	68	1.9	200
)	3,760	133	3.7	200
)	8,000	155	4.4	200
)	13,200	735	20.8	200
)	2,610	100	2.8	200

T SYSTEM COMPONENTS

Expendables					Enclosures			
Weight		Volume		Cost	Weight		Volume	
-yr	kg/w-yr	cu ft/w-yr	cu m/w-yr	$/w-yr	lbm/w-yr	kg/w-yr	cu ft/w-yr	cu m/w-yr
6	3	0.5	.01	47	84	38	2	.06
.A.	N.A.	N.A.	N.A.	26	88	40	7	.20
.A.	N.A.	N.A.	N.A.	39	130	59	14	.40
10	460	15.5	.40	430	740	340	15.5	.44
50	1,160	74	2.1	213	358	163	73	2.1
90	130	5	.14	125	272	124	13	.37

ACKNOWLEDGMENTS

The authors gratefully acknowledge the cooperation and encouragement of LCDR. Frank Anders of the U. S. Navy Bureau of Ships throughout the duration of this study. A number of individuals contributed useful state-of-the-art information on components of power systems. Some of those who contributed information on batteries are given as follows: Mr. H. B. Grohe, Wisco Division, The Electric Storage Battery Company; Mr. F. B. Pipal, National Carbon Company; Mr. M. F. Chubb, Eagle-Picher Company; Mr. R. Clock, Burgess Battery Co.; Mr. Howes, Exide Division, The Electric Storage Battery Company; Mr. A. Fleischer, Thomas A. Edison Research Laboratory; Messrs. T. O'Connor and A. Berger, Ionics, Inc. Data on fuel cells were obtained from Messrs. D. Douglas, E. A. Oster, and R. H. Blackmer, Accessory Aircraft Turbine Department, General Electric Company. Information on nuclear power systems was obtained from Capt. Robert Carpenter, U.S.A.F., Atomic Energy Commission; Mr. Banks, Martin Company; Prof. M. Benedict and Prof. C. D. Coryell, M.I.T.; Mr. M. Barmat, General Instrument Corp. Information on containers and vinyl plastic coatings was obtained from Mr. R. G. Cheatham, Materials Technology Inc. Mr. Saul of Avery and Saul Co. provided cost estimating information on fabricated steel vessels. Messrs. D. Whipple and Sapuppo, Instrumentation Laboratory, M.I.T. aided with information on low power generators. General information on energy conversion methods was given by Mr. B. J. Wilson and his group, Energy Conversion Branch, Naval Research Laboratory. To these persons and others, we are indebted, and their help is greatly appreciated.

BIBLIOGRAPHY

1. Betts, A. L., McCollum, P. A., "Unconventional Electrical Power Sources", WADC T.R. 54-409, September, 1954, A.S.T.I.A. No. A.D. 63967.

2. "Survey of Power Sources", Parts I and II, Armour Research Foundation, Contract No. W36-039-SC-32132, May, 1947, A.S.T.I.A. No. A.T.I. 1836771.

3. Proceedings of Seminar on "Advanced Energy Sources and Conversion Techniques" -- Volume I, under the auspices of the U. S. Army Signal Corps Contract No. DA-36-039 SC 78064, Pasadena, California, November, 1958, A.S.T.I.A. No. AD 209301.

4. Proceedings "13th Annual Power Sources Conference", Power Sources Division, U. S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey, April, 1959.

5. Maleev, V. L. "Machine Design," International Textbook Company, Scranton, 1939, p. 475.

A-1. "Some Plain Talk about Fuel Cells," General Electric Company.

A-2. Oster, E. A., "Cation-Exchange Membrane Fuel Cell Batteries" 14th Power Source Conference, Atlantic City, N.J., May 18, 1960.

F-1. Goff, R., "Long-Life, Fractional Horsepower Engine-Generator Power System," 5th Quarterly Report, Special Purpose Engine Company, Contract No. AF 30(635)-4490, 1957.

ANALYSES OF SELECTED SYSTEMS

Selection of Attractive Systems

Several systems, from the group studied in this survey, have been selected as offering the most assurance of development of reasonable mass produced systems within the time available. The necessary criteria to be considered in selection of such attractive systems are:

- State of development of technology
- Cost
- Use of critical materials
- Size
- Weight
- Detectability.

It is anticipated that large numbers of power systems with proven ability to supply electrical power continuously for a period of two years, may be required to be operational within five years in large numbers. Five years allows only sufficient time to design a prototype system, to test, to prove two year reliability, to refine the design, then to tool-up for mass production of a large number of the devices. This time schedule can be met only if the overall development time is minimized by use of only "off-the-shelf" components, concepts, techniques, and materials. Time is not available to permit investigation of speculative energy sources, conversion techniques, and the like, as part of the development of systems to be available in time to fill the initial needs.

Several other requirements must be met by systems judged to be most suitable for ultimate use. The large number of these devices contemplated makes it mandatory that they be low in cost. It is hoped that an adequate 2 watt 2 year system can be had at a mass production cost of less than $500, and it is certain that a price more than a few times this can not be tolerated. Similarly the use of scarce materials must be minimized, and preferably avoided altogether. The problems of transporting, handling, and anchoring the power systems require that their size and weight must be reasonable by marine shipping standards. These power systems should also be free from hazardous materials or effects lest their handling costs and difficulties become intolerably large. Finally, when the power systems have been placed in position in the oceans and are operating they should not be visible or otherwise easily detectable due to emission of noise, smoke, etc.

It is the considered opinion of Joseph Kaye and Company that of the systems surveyed, the following six presently offer the most assurance of development of reasonable devices which can be mass producible within five years:

Hydrogen-Oxygen Fuel Cell System
LeClanche Cell Battery System
Lead-Acid Battery System
Propane-Oxygen Thermoelectric System
Liquefied Gas Expansion System
Propane-Oxygen Internal Combustion Engine System

System Analyses

In the following sections, preliminary analyses and descriptions of six selected systems are presented. The system analyses are essentially a presentation of preliminary design data. These analyses do not represent any attempt to develop optimum designs for the six systems; thus the information presented should give a conservative indication of the potential of each of these six systems.

HYDROGEN-OXYGEN FUEL CELL SYSTEM

Principle of Operation

A fuel cell is a continuously-fed electro-chemical device in which the chemical energy of the reaction of air (or oxygen) and a conventional fuel is converted directly into electricity.

The ion-exchange fuel-cell can consume either the combination of hydrogen and oxygen, or of air and a hydrocarbon such as propane. Since the present application anticipates operation under water, the hydrogen-oxygen system is examined. The hydrogen and oxygen will be stored at high pressure and delivered to the cells at about 1 atm. pressure. The discharged product is water which is drained from the cells and retained within the encapsulating tank.

System Description and Operation

Figure A-1 shows the schematic arrangement of the necessary components for the fuel-cell system. According to the energy conversion matrix given in Fig. 1. his fuel cell system may be described as follows:

$$\text{Chemical Energy} \longrightarrow 43a \longrightarrow \text{Electrical Energy}$$

Fuel Cell

The fuel-cell system reported herein is based on the type of cells manufactured by General Electric Company. Each cell in the battery has an open circuit voltage of 1.23 volts, and will produce about 1 volt in the circuit. The ion-exchange membrane fuel-cell battery delivers 30 volts dc at 0.066 amperes (2 watts). The hydrogen and oxygen are stored at 6000 psig in spherical steel vessels. Pressure regulators reduce this pressure to

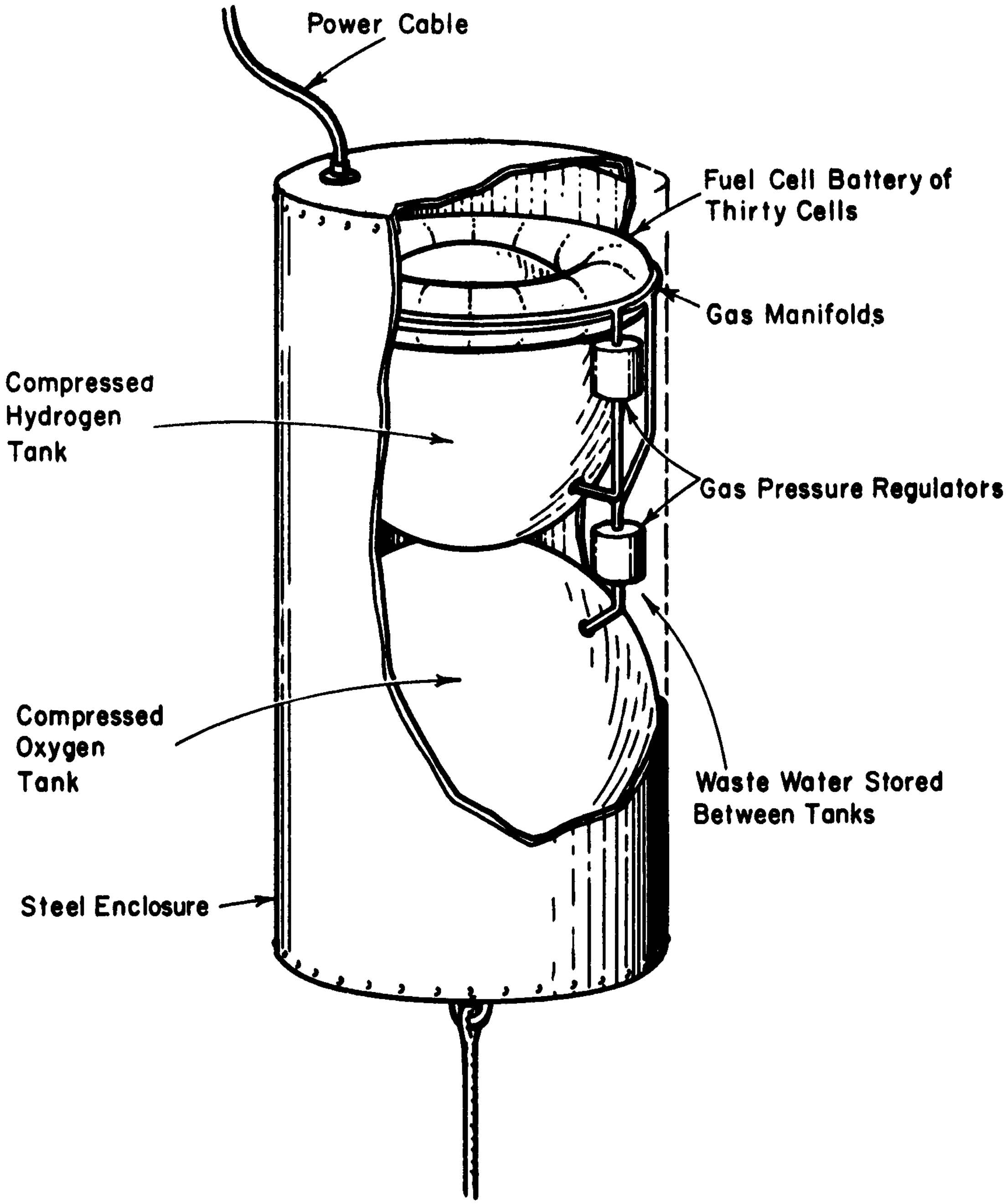

FIG. A-1 HYDROGEN-OXYGEN FUEL CELL SYSTEM approximately 1 atm, and the gases are fed to the battery, where they react in stoichiometric ratio to form liquid water. The liquid water drains from the battery by gravity. Control of the system is automatic and inherent. If no current is drawn from the battery, the gas pressures at the inlets of the cells rise slightly, and the pressure regulators stop the flow from the pressure tanks.

Since inert gases such as nitrogen and argon are present in small amounts in the less expensive, liquefied and distilled oxygen and will accumulate slowly, periodic purging of the cells is necessary. This purging is accomplished by a momentary puff of gases through the cell. This process does not significantly increase the fuel consumption. If desired, electrolytically-derived oxygen could be used to eliminate the need for purging the cells. However, electrolytically-derived oxygen is very expensive and is not considered for use here.

The entire system is hermetically sealed in a cylindrical container, which is vinyl coated for protection from corrosion.

The characteristics of the hydrogen-oxygen fuel cell system are given in Table A-1.

Discussion of System

The fuel cell, in its present state of development by General Electric Company and others, appears to be nearly ideal. Good dependability, highly efficient utilization of fuel, system simplicity, and sufficiently small size of conversion device are the assets of the fuel cell for use in either a 2 watt-2 year or a 5 watt-2 year power system. Although fuel cells can not yet be considered off-the-shelf hardware, it is believed that a prototype power system could be developed in a matter of months to be placed in operation for test in the ocean.

TABLE A-1

CHARACTERISTICS OF HYDROGEN-OXYGEN FUEL CELL SYSTEM

VALUE OF PARAMETER
Service: 2 watts for 2 years

PARAMETER	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	420 lbm	190 kg
Conversion-Device Weight	3.0 lbm	1.4 kg
Expendables Weight	25 lbm	10 kg
Buoyancy Force	-20 lbf	-9 kg
Conversion-Device Weight / Power Output	1.5 lbm/w	0.7 kg/w
Expendable Weight / Work Output	6.2 lbm / w yr	2.6 kg / w yr
Total System Displacement Volume	6 cu ft	0.16 cu m
Conversion-Device Volume	0.07 cu ft	0.0018 cu m
Expendables Volume	2.15 cu ft	0.058 cu m
Conversion-Device Volume / Power Output	0.03 cu ft / w	0.0008 cu m / w
Expendables Volume / Work Output	0.54 cu ft / w yr	0.00014 cu m / w yr
Total System Cost	$380	$380
Conversion-Device Cost	$100	$100
Expendables Cost	$7	$7
Conversion-Device Cost / Power Output	$50 / w	$50 / w
Expendables Cost/Work Output	$1.80/w yr	$1.80/w yr
Heat-Source Temperature	NA R	NA K
Heat-Sink Temperature	NA R	NA K
Carnot Efficiency	NA %	NA %
Overall Efficiency	75 %	75 %
Voltage Output of Conversion Device	NA vac 30 vdc	NA vac 30 vdc
Current Output of Conversion Device	0.066 amp	0.066 amp

TABLE A-1

CHARACTERISTICS OF HYDROGEN-OXYGEN FUEL CELL SYSTEM

VALUE OF PARAMETER

Service: 5 watts for 2 years

PARAMETER	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	1040 lbm	470 kg
Conversion-Device Weight	7.5 lbm	3.5 kg
Expendables Weight	62.0 lbm	28 kg
Buoyancy Force	-80 lbf	-36 kg
Conversion-Device Weight / Power Output	1.5 lbm/w	0.7 kg/w
Expendables Weight / Work Output	6.2 lbm / w yr	2.6 kg / w yr
Total System Displacement Volume	15 cu ft	0.4 cu m
Conversion-Device Volume	0.17 cu ft	0.0047 cu m
Expendables Volume	5.4 cu ft	0.15 cu m
Conversion-Device Volume / Power Output	0.03 cu ft / w	0.0008 cu m / w
Expendables Volume / Work Output	0.54 cu ft / w yr	0.00014 cu m / w yr
Total System Cost	$660	$660
Conversion-Device Cost	$100	$100
Expendables Cost	$18	$18
Conversion-Device Cost / Power Output	$20 / w	$20 / w
Expendables Cost/Work Output	$1.80/w yr	$1.80/w yr
Heat-Source Temperature	NA R	NA K
Heat-Sink Temperature	NA R	NA K
Carnot Efficiency	NA %	NA %
Overall Efficiency	75 %	75 %
Voltage Output of Conversion Device	NA vac 30 vdc	NA vac 30 vdc
Current Output of Conversion Device	0.170 amp	0.170 amp

Reliability of hydrogen-oxygen ion membrane fuel cells has been proven by General Electric Company in life tests for periods up to one and one half years. Manufacturing methods for mass production are being developed. The only critical material in this fuel cell is the catalyst. The need for periodic purging of the cell to remove inert gases would not significantly increase fuel consumption and does not appear to present a difficult development problem. A simple on-off valve could be used for purging and would be opened for a few seconds at intervals of several days.

The system weights, dimensions and costs estimates presented here are made on conservative bases. Significant reductions in these parameters are possible by measures such as integration of the fuel tanks and the system container and by the use of high strength materials.

No fuel-cell information was obtained from organizations other than General Electric Company. The mission of this study was to consider the feasibility of various power systems rather than optimize any of these systems. The General Electric Company supplied adequate data, based on experiments, to fulfill the requirements of this study. Examination of the comparative merits of fuel cells under development by various organizations should be performed as a step in optimizing the weight, volume, cost, reliability, and logistics of a protytype model.

Calculation Methods for System

The parameters which control the size of the fuel cell are power requirements and the desired cell life. Tests at the General Electric Company indicate that the parameter, cell life, multiplied by the current produced per unit of cell area, is roughly constant. This parameter generally has a value of between 30 and 50 amp hr/sq cm in the tests which have been performed. Although a value of 10 amp hr/sq cm has been mentioned by General Electric personnel for high reliability, we have used a value of 50 amp hr/sq cm in making estimates herein. The reason for this higher value of the cell-life parameter is the rapid progress in fuel cell research. Even if the lower value of 10 amp hr/sq cm were used as the design parameter, there would be but small increases in the weight and size of the system. The cost would probably be increased because a larger battery would be required. However, since the present price figures are tentative, no estimate of the increase in cost can be attempted now.

The value of current flux for the fuel cells is 0.003 amp/sq cm, based on the value of the cell-life parameter of 50 amp hr/sq cm. The resultant volume of the fuel-cell battery is 0.07 cu ft.

The efficiency of a fuel cell of this type would be 76% when operated with a voltage in the circuit of approximately 1 volt. This value of efficiency is multiplied by the free energy charge at constant temperature (or the heat of combustion) of the reactants to give the specific power output (Btu/lbm or watt hr/kg) of the fuel cell. The formula for the efficiency of the fuel cell is given as follows:

$$\text{Efficiency} = (\text{Cell Voltage}/\text{Cell Open Circuit Voltage}) - 0.05$$

The factor, 0.05 pertains to the General Electric type of fuel cell.

The high pressure vessels, for containing the hydrogen and oxygen at 6000 psi, have a working stress of 50,000 psi. The system container is 3/16 in. steel with a vinyl coating. The container design is buckling limited at a depth of 200 ft.

Because of its small size, the cost of the fuel cell was held constant for both the 2 watt and the 5 watt power requirement cases. It is reasoned that in large size cells, the cost will be directly related to the power requirement; however, in the small size cells, the per-unit cost of cells will be fairly constant regardless of output.

TABLE A-2

DETAILED ESTIMATES OF COSTS AND WEIGHTS OF COMPONENTS

OF HYDROGEN-OXYGEN FUEL CELL SYSTEM

2 watts for 2 years

Item	Cost ($)	Wt. (lbm)	Vol. (cu ft)
Battery	100	3	0.07
Hydrogen	5	2.8	1.43
Oxygen	2	22	0.72
Hydrogen Tank	62	124	-
Oxygen Tank	32	64	-
Regulators	50	10	-
Enclosure	125	200	6
Total	380	425	

LECLANCHE CELL BATTERY SYSTEM

Principle of Operation

The LeClanche cell battery system contains individual cells, similar to those used in ordinary flashlights, in which chemical energy is stored. When the cells are connected electrically together and to a load, the stored chemical energy is converted into electricity by the chemical reactions which occur. The cells are arranged in a circuit which will provide the desired electrical output directly.

System Description and Operation

The LeClanche cell battery system is illustrated in Fig. B-1 and may be described by the energy-conversion matrix of Fig. 1 as follows:

$$\text{Chemical Energy} \longrightarrow \underset{\text{Battery}}{43b} \longrightarrow \text{Electrical Energy}$$

The LeClanche cell consists of a zinc anode, a manganese dioxide cathode, and an electrolyte consisting of a combination of ammonium chloride and zinc chloride. An example of one of the several important reactions for producing electricity in a LeClanche cell is the following:

$$Zn + 2MnO_2 \longrightarrow ZnO \cdot Mn_2O_3$$

Another important reaction in the LeClanche cell causes the generation of hydrogen gas. To suppress the possibility of an explosion, the container would be inerted with nitrogen at a pressure of 100 psia.

The LeClanche cell battery system reported here would require 475 No. 6 igniter cells connected in series and parallel to obtain 2 watts throughout the 2 year running time of the system. Although the packaging

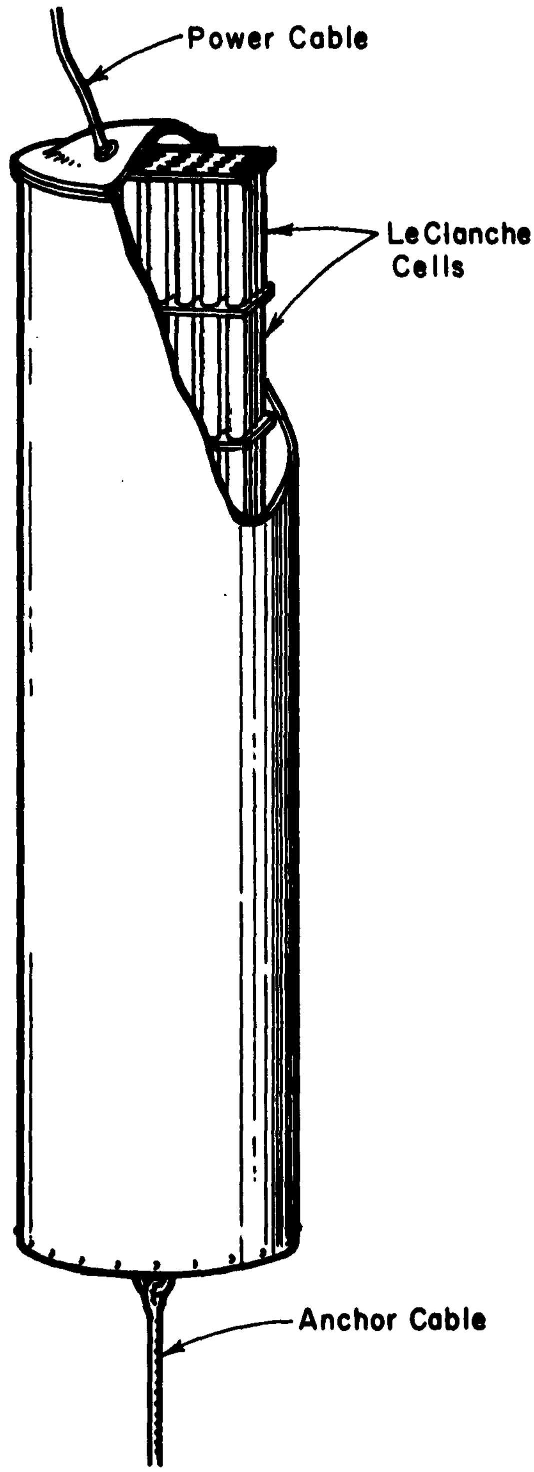

FIG. B-1   LECLANCHE CELL BATTERY SYSTEM of the cells can be varied considerably because their operation is independent of orientation, the feasibility design is based on 12 tiers of cells with 40 batteries in each tier. Such an arrangement would require a cylindrical steel container with a diameter of 25 in., a height of 8.5 ft and a weight of 360 lbm to accommodate the 2 watts, 2 years application. The container would have a coating of vinyl plastic for protection against sea-water corrosion.

The characteristics of the LeClanche cell battery system are given in Table B-1.

Discussion of System

The design given here for a LeClanche cell battery system is based on off-the-shelf hardware. Information was obtained from National Carbon Company about the parameters such as size, weight, output, and reliability. The No. 6 type of cell used for this study was designed for general use and cannot be considered as optimum for this oceanic application in terms of compact packaging, high reliability, or large output per unit mass. However, the Coast Guard is presently performing reliability tests on especially designed LeClanche cell batteries.

The voltage of the individual cells has been assumed here to degrade from an initial value of 1.5 v. to a final value of 0.9 v. at the end of 2 years. This variation in voltage is greater than the allowable 10 percent specified. One method of controlling the voltage would require that the number of cells be increased by at least 100 percent. A second method involves the use of a voltage control device such as a solid state converter or an adjustable dropping resistor. Neither of the above methods of reducing voltage variations is included in weight, volume, and cost estimates of the LeClanche cell battery system reported here. The addition of a voltage

TABLE B-1

CHARACTERISTICS OF LECLANCHE CELL BATTERY SYSTEM

VALUE OF PARAMETER

Service: 2 watts for 2 yrs

PARAMETER	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	1770 lbm	800 kg
Conversion-Device Weight	1010 lbm	460 kg
Expendables Weight	NA lbm	NA kg
Buoyancy Force	100 lbf	45 kg
Conversion-Device Weight / Power Output	.500 lbm/w	.230 kg/w
Expendable Weight / Work Output	NA lbm/w yr	NA kg/w yr
Total System Displacement Volume	29 cu ft	0.81 cu m
Conversion-Device Volume	10 cu ft	0.28 cu m
Expendables Volume	NA cu ft	NA cu m
Conversion-Device Volume / Power Output	. 5 cu ft/w	0.14 cu m/w
Expendables Volume / Work Output	NA cu ft/w yr	NA cu m/w yr
Total System Cost	$830	$830
Conversion-Device Cost	$360	$360
Expendables Cost	$NA	$NA
Conversion-Device Cost / Power Output	$180 /w	$180 /w
Expendables Cost/Work Output	$NA/w yr	$NA/w yr
Heat-Source Temperature	NA R	NA K
Heat-Sink Temperature	NA R	NA K
Carnot Efficiency	NA %	NA %
Overall Efficiency	NA %	NA %
Voltage Output of Conversion Device	28.5 vdc	28.5 vdc
Current Output of Conversion Device	.07 amp	.07 amp

TABLE B-1

CHARACTERISTICS OF LECLANCHE CELL BATTERY SYSTEM

VALUE OF PARAMETER

Service: 5 watts for 2 yrs

PARAMETER	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	4300 lbm	1960 kg
Conversion-Device Weight	2520 lbm	1150 kg
Expendables Weight	NA lbm	NA kg
Buoyancy Force	50 lbf	22 kg
Conversion-Device Weight / Power Output	.500 lbm/w	.230 kg/w
Expendable Weight / Work Output	NA lbm/w yr	NA kg/w yr
Total System Displacement Volume	68 cu ft	1.9 cu m
Conversion-Device Volume	25 cu ft	0.7 cu m
Expendables Volume	NA cu ft	NA cu m
Conversion-Device Volume / Power Output	. 5 cu ft/w	. 0.14 cu m/w
Expendables Volume / Work Output	NA cu ft/w yr	NA cu m/w yr
Total System Cost	$1920	$1920
Conversion-Device Cost	$900	$900
Expendables Cost	$NA	$NA
Conversion-Device Cost / Power Output	$180 /w	$180 /w
Expendables Cost/Work Output	$NA/w yr	$NA/w yr
Heat-Source Temperature	NA R	NA K
Heat-Sink Temperature	NA R	NA K
Carnot Efficiency	NA %	NA %
Overall Efficiency	NA %	NA %
Voltage Output of Conversion Device	28.5 vdc	28.5 vdc
Current Output of Conversion Device	.07 amp	.07 amp

control device to the system would not affect the feasibility, weight, or volume of the system appreciably; however, there would be a minor increase in the total cost reported in Table B-1.

Calculation Methods for System

The specifications of No. 6 igniter cells which have been used as a basis of this feasibility design are given as follows:

Cell weight	2.13 lbm
Cell diameter	2.88 in.
Cell length	6.88 in.
Cell volume	0.034 cu ft
Cell cost	$0.75

The number of cells required depends on the operating temperature, the total power requirement, the desired life, and the allowable degradation in cell voltage. The relationships of these variables is determined by experment. Based on the requirements of this study, 475 of the No. 6 cells would be required at a temperature of 50 F during discharge.

The weight of racks for packaging the cells and of wiring is based on a value of 3/4 lbm per cell. The cost of such racks and wiring is assumed to be $0.25 per cell.

Because of the pressure of the nitrogen gas for inerting the interior of the container, the design criterion which applies at depths from sea level to 200 ft is that for simple tension in the container wall at sea level. At this depth, the pressure inside the container is 85 psi above ambient pressure. A cylindrical, vinyl-coated container was designed accordingly.

LEAD-ACID BATTERY SYSTEM

Principle of Operation

The lead-acid battery system consists of individual cells, similar to those used in automobile batteries, in which chemical energy is stored. When the cells are placed in an electrical circuit, the chemical energy is converted into electrical energy. The cells are arranged in series and parallel to obtain the desired electrical output directly.

System Description and Operation

The lead-acid battery system is illustrated in Fig. C-1 and may be described by the energy-conversion matrix of Fig. 1 as follows:

$$\xrightarrow{\text{Chemical Energy}} \underset{\text{Battery}}{43b} \xrightarrow{\text{Electrical Energy}}$$

Each cell is comprised of a lead anode, a lead oxide cathode, and a sulfuric acid electrolyte. The principal chemical reaction is given by the equation

$$\underset{\text{Anode}}{PbO_2} + \underset{\text{Cathode}}{Pb} + \underset{\text{Electrolyte}}{2\,H_2SO_4} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2\,PbSO_4 + 2H_2O$$

The system of Fig. C-1 consists of 33 Willard type DHB5-1 cells mounted in special clamping racks and enclosed in a vinyl coated cylinder. The batteries are connected in parallel and series combinations to give the desired output voltage.

Since hydrogen gas is evolved during cell discharge, no oxygen must be present inside the container. In buoys powered by lead-acid batteries,

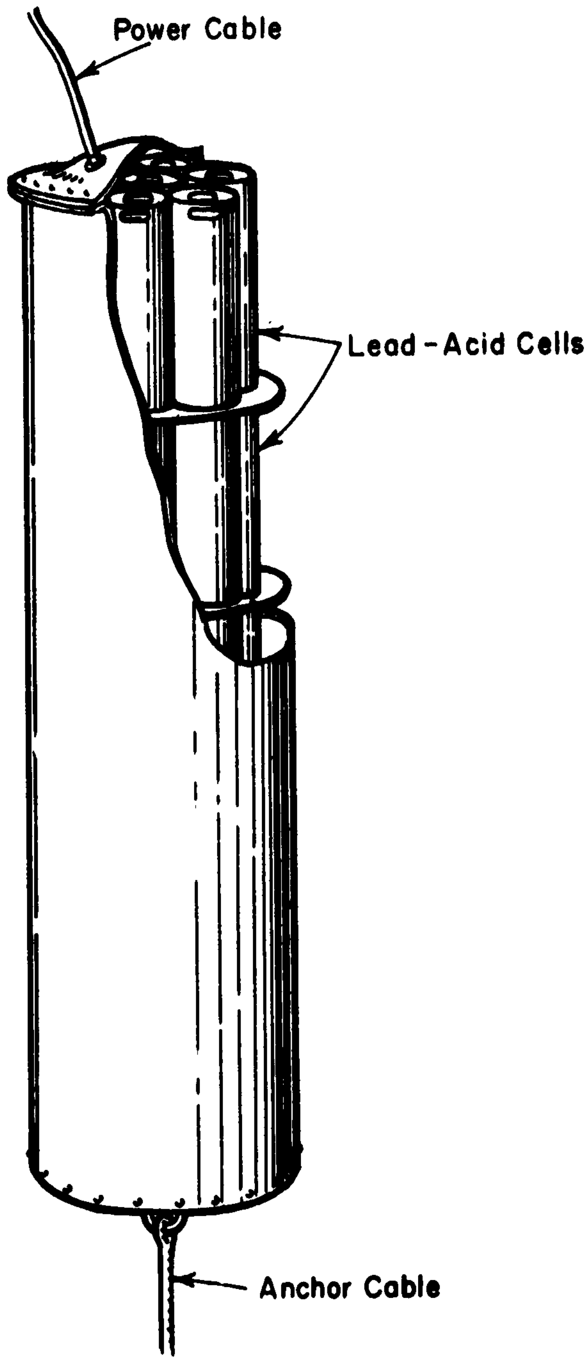

FIG. C-1 LEAD-ACID BATTERY SYSTEM

this problem has been solved by venting the evolved hydrogen overboard. Because of the requirements in the present study for operation of all power systems at a depth of 200 ft, the evolved hydrogen must be retained on board. Therefore, it was assumed that the container would be inerted with nitrogen at a pressure of 100 psia.

Based on the use of lead-acid cells of the DHB5-1 type, a five tier cell arrangement has been designed. Such an arrangement would have 7 cells in each of 3 of the tiers and 6 cells in each of the remaining 2 tiers. This cell arrangement would require for the 2 watts, 2 years application, a cylindrical container with a diameter of 30 in., a height of 11 ft, and a weight of 525 lbm. The container would have a coating of vinyl plastic for protection against sea-water corrosion.

The characteristics of the lead-acid battery system are given in Table C-1.

A variation of the above lead-acid battery system was analyzed which would use "dry charged" cells. These dry charged cells would be energized sequentially by the addition of electrolyte to groups of cells.

This type of system was found to be unsuitable since successful operation depends on electrical charging of the battery to the fully charged condition subsequent to the addition of electrolyte. Without the additional electrical charging, only 65 to 70 per cent of full power is available. This lower power output, together with a complex control system for switching and energizing the batteries would more than double the weight and volume of the power system and would simultaneously decrease its reliability.

TABLE C-1

CHARACTERISTICS OF LEAD-ACID BATTERY SYSTEM

VALUE OF PARAMETER

Service: 2 watts for 2 yrs

PARAMETER	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	3350 lbm	1520 kg
Conversion-Device Weight	2740 lbm	1250 kg
Expendables Weight	NA lbm	NA lbm
Buoyancy Force	175 lbf	79.5 kg
Conversion-Device Weight / Power Output	1370 lbm/w	.630 kg/w
Expendable Weight / Work Output	NA lbm/w yr	NA kg/w yr
Total System Displacement Volume	55 cu ft	1.54 cu m
Conversion-Device Volume	24.8 cu ft	.7 cu m
Expendables Volume	NA cu ft	NA cu m
Conversion-Device Volume / Power Output	12.4 cu ft/w	0.35 cu m/w
Expendables Volume / Work Output	NA cu ft/w yr	NA cu m/w yr
Total System Cost	$1680	$1680
Conversion-Device Cost	$1390	$1390
Expendables Cost	$NA	$NA
Conversion-Device Cost / Power Output	$700/w	$700/w
Expendables Cost/Work Output	$NA/w yr	$NA/w yr
Heat-Source Temperature	NA R	NA K
Heat-Sink Temperature	NA R	NA K
Carnot Efficiency	NA %	NA %
Overall Efficiency	NA %	NA %
Voltage Output of Conversion Device	28 vdc	28 vdc
Current Output of Conversion Device	.072 amp	.072 amp

TABLE C-1

CHARACTERISTICS OF LEAD-ACID BATTERY SYSTEM

VALUE OF PARAMETER

Service: 5 watts for 2 yrs

PARAMETER	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	8300 lbm	3760 kg
Conversion-Device Weight	6720 lbm	3040 kg
Expendables Weight	NA lbm	NA kg
Buoyancy Force	220 lbf	100 kg
Conversion-Device Weight / Power Output	1350 lbm/w	610 kg/w
Expendable Weight / Work Output	NA lbm/w yr	NA kg/w yr
Total System Displacement Volume	133 cu ft	3.68 cu m
Conversion-Device Volume	61 cu ft	1.7 cu m
Expendables Volume	NA cu ft	NA cu m
Conversion-Device Volume / Power Output	12.2 cu ft/w	0.34 cu m/w
Expendables Volume / Work Output	NA cu ft/w yr	NA cu m/w yr
Total System Cost	$4100	$4100
Conversion-Device Cost	$3400	$3400
Expendables Cost	$NA	$NA
Conversion-Device Cost / Power Output	$680/w	$680/w
Expendables Cost/Work Output	$NA/w yr	$NA/w yr
Heat-Source Temperature	NA R	NA K
Heat-Sink Temperature	NA R	NA K
Carnot Efficiency	NA %	NA %
Overall Efficiency	NA %	NA %
Voltage Output of Conversion Device	28 vdc	28 vdc
Current Output of Conversion Device	.071 amp	.071 amp

Discussion of System

The lead-acid battery system reported herein is based on off-the-shelf hardware. The Willard DHB5-1 cell was developed for long life use in signal buoy applications. These cells have been used for powering signal buoys since one of the first such installations at Minot's Light off Cape Cod in 1934. Power and industrial companies have used the industrial Willard DH5-1 cell in circuit breaker and control applications where two year cycles are not uncommon. An advantage of such cells would be their recharge and re-use potential of 5 to 7 cycles.

Wisco Division of the Electric Storage Battery Company has under development a 6 volt 3,000 amp-hour battery designed for buoy applications with high power requirements. This battery is designed for a two year cycle and is approximately 22 in. in diameter and 54 in. high, weighing 1300 lbm.

Calculation Methods for System

The specifications of the Willard DHB5-1 metal-encased, charge-retaining cells which have been used as a basis of this feasibility design are given as follows:

Cell weight	83 lbm
Cell diameter	9.25 in.
Cell length	19.25 in.
Cell net volume	0.75 ft^3
Cell output	600 amp hr at 2 volts
Cell cost	$42
Self discharge in 2 years	10% of initial useful charge

The effective cell output is reduced by the self discharge. The required number of cells can be determined directly from the cell characteristics given above and the power requirements of the system. The cell voltage decreases from a value of approximately 2.15 volts initially, to about 1.9 volts at the end of 2 years.

The weight of racks for packaging the cells and of wiring is based on a value of 3 lbm per cell. The cost of providing such racks and wiring in this system is assumed to be $3 per cell.

Because of the nitrogen for inerting the interior of the container, the criterion which applies for the container design at depths from sea level to 200 ft is that for simple tension in the container wall at sea level. The pressure inside the container is 85 psi above ambient pressure at sea level. A cylindrical, vinyl-coated container was designed accordingly.

PROPANE-OXYGEN THERMOELECTRIC SYSTEM

Principle of Operation

In the propane-oxygen thermoelectric system, chemical energy, stored in oxygen and propane, is released as thermal energy during combustion. The thermal energy, or heat, is received by a thermoelectric generator which generates electricity and rejects a portion of the heat received to the environment. The thermoelectric generator portion of the system consists of p- and n-type semiconductor thermoelements which are arranged in an array of series-connected thermocouples.

System Description and Operation

The propane-oxygen thermoelectric system is illustrated in Fig. D-1 and may be described by the energy-conversion matrix of Fig. 1 as follows:

Chemical Energy		Thermal Energy		Electrical Energy		Electrical Energy
⟶	29a	⟶	47a	⟶	49a	⟶
	Combustor		Thermopile		Inverter	

In this system, propane is burned with oxygen and the thermal energy of this combustion is used to heat the hot junction of a lead telluride thermopile. The cold junctions of the thermopile are cooled by heat-dissipation fins that extend into the surrounding sea. The propane is stored as liquid in a spherical vessel designed for medium pressures, while the oxygen is stored as gas at 6000 psi in a spherical vessel designed for high pressures. A third spherical tank contains calcium oxide to absorb the products of combustion, carbon dioxide and water vapor. This tank is not shown in Fig. D-1. The calcium oxide is slowly converted into calcium hydroxide and calcium carbonate. The three tanks in this system are exposed to the sea and would have a vinyl plastic coating to resist corrosion.

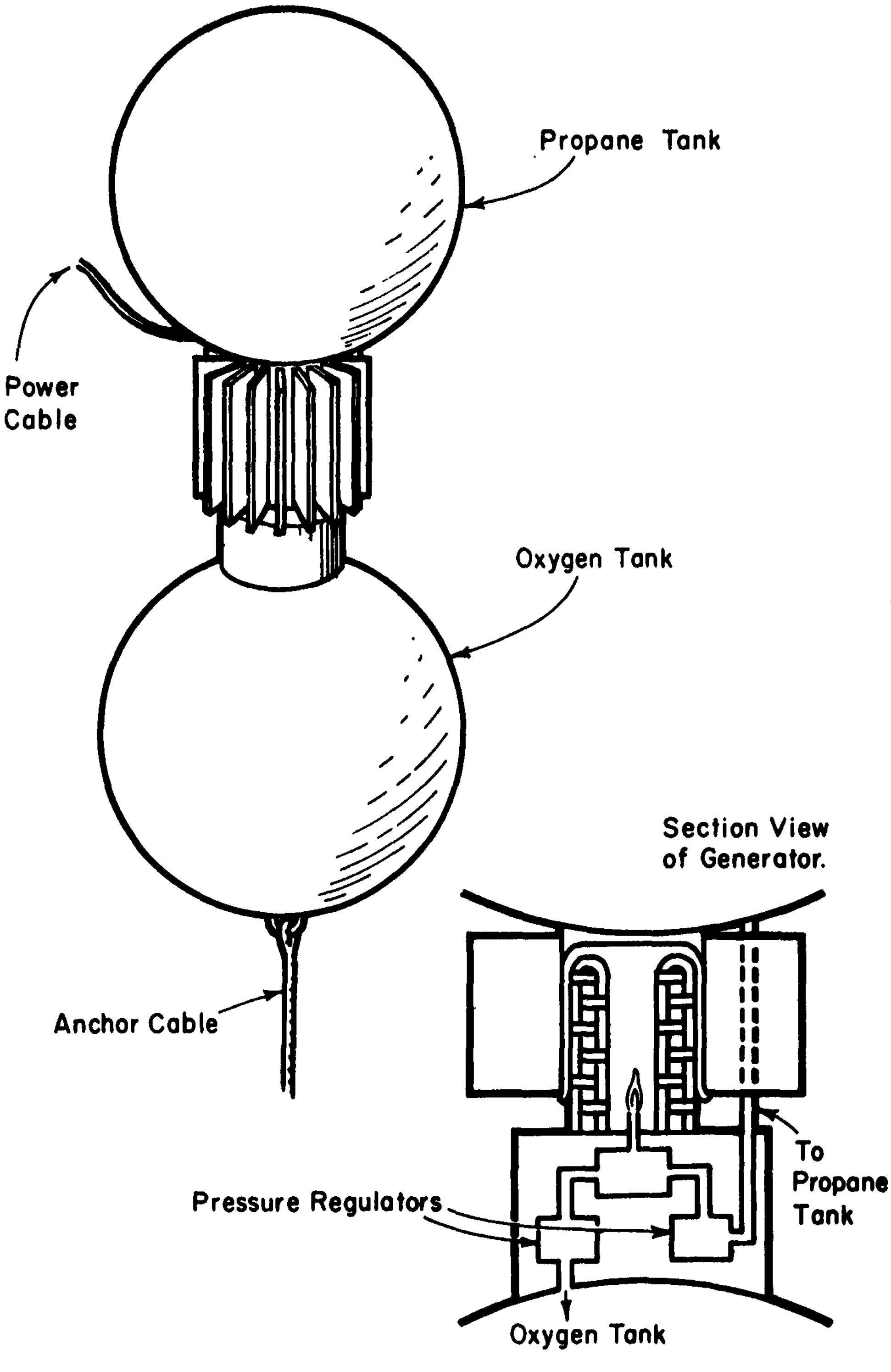

FIG. D-1 PROPANE-OXYGEN THERMOELECTRIC SYSTEM

There are three thermoelectric generators which provide the basis for the design of the propane-oxygen thermoelectric system reported here. These three generators were designed to consume propane and air. The first of these generators was developed by General Instrument Corporation to provide 5 watts for 1 year. The second of these generators is the Westinghouse TAP-100 generator which produces 100 watts and weighs 40 lbm. The third generator is the Bell "power pole" which uses chromel-constantan thermocouples, produces 1 watt at 25 volts, and is designed for unattended operation for 1 year.

The output voltage of the thermopile for the propane-oxygen thermoelectric system is 2.8 volts. A solid-state converter is required to increase this voltage to 28 volts.

For the 2 watts, 2 years application, the oxygen tank would have a diameter of 3.9 ft and a weight of 2700 lbm, the propane tank would have a diameter of 2.5 ft and a weight of 100 lbm, and the calcium oxide tank would have a diameter of 3.7 ft and a weight of 220 lbm.

The characteristics of the propane-oxygen thermoelectric system are given in Table D-1.

Discussion of System

The propane-oxygen thermoelectric system appears to be a reliable power system for oceanic use. The cost of thermoelectric devices today is very high, mainly because the production rates are low. For example, General Instruments Corporation has stated that if their generator for 5 watts for 1 year were mass produced, the cost of this generator could be reduced from $5000 to $500.

The relatively low efficiency of thermoelectric energy conversion

TABLE D-1

CHARACTERISTICS OF PROPANE-OXYGEN THERMOELECTRIC SYSTEM

PARAMETER	VALUE OF PARAMETER Service: 2 watts for 2 years English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	7100 lbm	3200 kg
Conversion-Device Weight	40 lbm	18 kg
Expendables Weight	4050 lbm	1850 kg
Buoyancy Force	-3200 lbf	-1450 kg
Conversion-Device Weight / Power Output	20 lbm/w	9 kg/w
Expendable Weight / Work Output	1010 lbm / w yr	460 kg / w yr
Total System Displacement Volume	63 cu ft	1.8 cu m
Conversion-Device Volume	1 cu ft	0.03 cu m
Expendables Volume	62 cu ft	1.8 cu m
Conversion-Device Volume / Power Output	0.5 cu ft / w	0.01 cu m / w
Expendables Volume / Work Output	15.5 cu ft / w yr	0.4 cu m / w yr
Total System Cost	$2400	$2400
Conversion-Device Cost	$500	$500
Expendables Cost	$144	$144
Conversion-Device Cost / Power Output	$250 / w	$250 / w
Expendables Cost/Work Output	$36/w yr	$36/w yr
Heat-Source Temperature	1450 R	800 K
Heat-Sink Temperature	540 R	300 K
Carnot Efficiency	63 %	63 %
Overall Efficiency	2.25 %	2.25 %
Voltage Output of Conversion Device	NA vac 2.8 vdc	NA vac 2.8 vdc
Current Output of Conversion Device	0.7 amp	0.7 amp

TABLE D-1

CHARACTERISTICS OF PROPANE-OXYGEN THERMOELECTRIC SYSTEM

VALUE OF PARAMETER

Service: 5 watts for 2 years

PARAMETERS	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	17,600 lbm	8000 kg
Conversion-Device Weight	40 lbm	18 kg
Expendables Weight	10,100 lbm	4600 kg
Buoyancy Force	-7900 lbf	-3600 kg
Conversion-Device Weight / Power Output	8 lbm/w	4 kg/w
Expendable Weight / Work Output	1010 lbm / w yr	460 kg / w yr
Total System Displacement Volume	155 cu ft	4.4 cu m
Conversion-Device Volume	1 cu ft	0.03 cu m
Expendables Volume	154 cu ft	4.3 cu m
Conversion-Device Volume / Power Output	0.2 cu ft / w	0.006 cu m / w
Expendables Volume / Work Output	15.5 cu ft / w yr	0.4 cu m / w yr
Total System Cost	$5200	$5200
Conversion-Device Cost	$500	$500
Expendables Cost	$360	$360
Conversion-Device Cost / Power Output	$100 / w	$100 / w
Expendables Cost/Work Output	$36/w yr	$36/w yr
Heat-Source Temperature	1450 R	800 K
Heat-Sink Temperature	540 R	300 K
Carnot Efficiency	63 %	63 %
Overall Efficiency	2.25 %	2.25 %
Voltage Output of Conversion Device	NA vac 4 vdc	NA vac 4 vdc
Current Output of Conversion Device	1.3 amp	1.3 amp

results in large costs, weights, and volume of tanks, fuel, oxidant, and exhaust-absorbing material. Because of this low efficiency, the potential of this system increases greatly either if the system could be operated with atmospheric air instead of stored oxygen, or if the exhaust could be expelled oberboard. The weights of calcium oxide and of oxygen and both the weight and the cost of the oxygen tank comprise large fractions of the total values of these system parameters.

Calculation Methods for System

It is assumed that the thermoelectric generator would use lead telluride thermoelements possessing the following properties:

Seebeck coefficient, $\alpha = \pm 200$ volts/C

Electrical resistivity, $\rho = 10^{-3}$ ohm cm

Thermal conductivity, $k = 4 \times 10^{-2}$ watts/cm C

It is also assumed that the above properties are independent of temperature. These properties can be used to estimate the characteristics of a system to produce 28 volts as shown in Table D-2, below.

TABLE D-2

GENERATOR DESIGN PARAMETERS

Temperature Difference C	Emf/Couple volts/couple	No. of Couples	Length/Cross-Section Area cm^{-1}
400	0.16	175	70
500	0.20	140	70
600	0.24	117	70
700	0.28	100	70
800	0.32	88	70

The ratio of thermoelement length to cross sectional area of 70 cm^{-1}, given in Table D-2, appears to be unreasonably large. Therefore, this ratio is assumed to have the reduced value of 7 cm^{-1}. It follows that the thermopile would have the following properties at a temperature difference of 500 C:

Length/Cross-Section Area	7 cm^{-1}
No. of Couples	14
Emf/Couple	0.20 volts
Thermopile Voltage	2.8 volts

Based on current performance, the efficiency of the thermoelectric generator is assumed to be 5 per cent. It is assumed that 60 per cent of the chemical energy available from the combustion of propane and oxygen reaches the thermopile hot junctions. A conversion efficiency of 75 per cent is reasonable for the electrical converter which steps the generator output voltage of 2.8 volts up to a value of 28 volts. Therefore, the overall conversion efficiency of 2.25 per cent is obtained for the conversion of chemical energy into electrical energy at the required voltage.

Until recently the price of bismuth telluride, Bi_2Te_3, thermocouples was quoted at $125 per couple. Recently couples have been advertised at $35 per couple. This latter price is possibly still an inflated value due to lack of competition and low rates of production in the manufacture of semiconductor thermocouples. General Instrument Corporation has stated that their 5 watt thermoelectric system could be sold for $500 if mass produced. In view of these prices, a cost of $500 seems reasonable for the thermoelectric generator for the power system of interest here.

The cost of oxygen is assumed to be $0.10 per lbm, and the cost of propane is assumed to be $0.05 per lbm. The cost of calcium oxide is assumed to be $0.01 per lbm. The excess of calcium oxide above the stoichiometric quantity will be 10 per cent. The calcium oxide will be packed in the tank at a density of 100 lbm per cu ft.

The high pressure vessel for storage of oxygen is designed for an internal pressure of 6000 psi. Throughout the range of depths from sea level to 200 ft, the "worst case" depth for the propane vessel design is at sea level, where the internal pressure is about 80 psi above atmospheric pressure. The design criterion for the calcium oxide tank is for compression loading at the 200 ft depth.

A cost of $70 has been assumed for a solid-state converter to increase the output voltage of the thermoelectric generator from 2.8 volts to 28 volts.

LIQUEFIED GAS EXPANSION SYSTEM

Principle of Operation

In the liquefied gas expansion system, heat from the ocean is used to boil liquid ammonia. The ammonia vapor evolved is used to drive a small reciprocating expansion engine. The expansion engine, in turn, drives an electrical generator to produce the required output. The vapor exhausted from the expansion engine is absorbed in water which is stored on board. In this system, the expansion engine operates continuously.

System Description and Operation

The liquefied gas expansion system is illustrated in Fig. E-1 and may be described by the energy-conversion matrix of Fig. 1 as follows:

Thermal Energy	Thermal Energy	Mechanical Energy	Electrical Energy
$\longrightarrow$ 33b	$\longrightarrow$ 19a	$\longrightarrow$ 45a	$\longrightarrow$
Boiler	Expansion Engine	Generator	

The liquid ammonia would be contained in a spherical tank with a diameter of 5.8 ft and a weight of 550 lbm for the 2 watts, 2 years application. The water for absorption of the ammonia would be contained in a second spherical tank with a diameter of 7.1 ft and a weight of 920 lbm for the 2 watts, 2 years application. These tanks are exposed to the ocean and would be coated with vinyl plastic.

The control requirements of this system are very moderate. The system requires a pressure regulator valve after the expansion engine to maintain a constant exhaust pressure despite the variations in the pressure in the water tank.

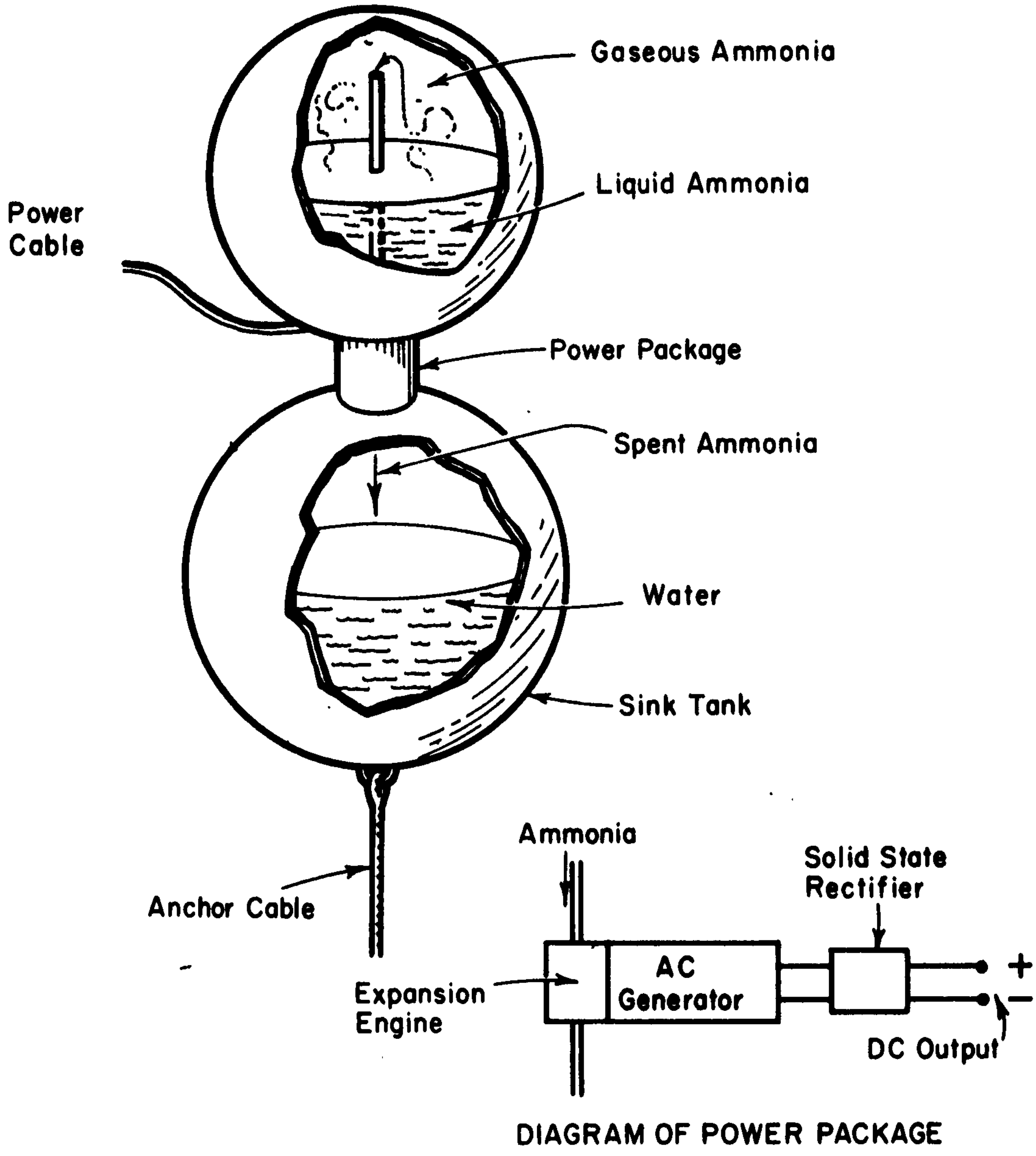

FIG. E-1 AMMONIA EXPANSION ENGINE SYSTEM

The expansion engine would run continuously and would be of the reciprocating type, employing the combination of a piston driving a crankshaft. The bore and stroke for a "square" configuration would be about 0.43 in. for an engine speed of 1000 rpm.

The characteristics of the liquefied gas expansion system are given in Table E-1, on the following page.

Two alternative systems based on the expansion of liquefied ammonia offer interesting improvements over the basic system. In the first of these alternative systems, concrete is substituted for steel as the tank material. In the second of these alternative systems, the steel tanks are retained, but the exhaust from the expansion engine is vented overboard through a long tube extending upward nearly to the surface of the sea. In the first alternative system (concrete tanks), the system cost is reduced greatly because of the low price of concrete compared with that of steel. However, the system weight does increase slightly with the use of concrete tanks. In the second alternative system (open system), the system cost, weight, and volume are all decreased because the water tank is eliminated. The basic system is compared with the two alternative systems in Table E-2.

TABLE E-2

COMPARISON OF LIQUEFIED AMMONIA EXPANSION SYSTEMS TO OBTAIN 2 WATTS FOR 2 YEARS

	Cost $	Total Weight lbm	Total Volume cu ft
Closed System, Steel Tanks	1,050	11,700	295
Closed System, Concrete Tanks	380	12,400	295
Open System, Steel Tanks	575	4,600	105

TABLE E-1

CHARACTERISTICS OF LIQUEFIED GAS EXPANSION SYSTEM

VALUE OF PARAMETER

Service: 2 watts for 2 years

PARAMETER	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	11,700 lbm	5300 kg
Conversion-Device Weight	10 lbm	4 kg
Expendables Weight	10,200 lbm	4600 kg
Buoyancy Force	7,000 lbf	3200 kg
Conversion-Device Weight / Power Output	5 lbm/w	2 kg/w
Expendable Weight / Work Output	2550 lbm/w yr	1160 kg/w
Total System Displacement Volume	294 cu ft	8.3 cu m
Conversion-Device Volume	1 cu ft	0.028 cu m
Expendables Volume	293 cu ft	8.3 cu m
Conversion-Device Volume / Power Output	0.5 cu ft / w	0.014 cu m / w
Expendables Volume / Work Output	733 cu ft / w yr	2.1 cu m / w yr
Total System Cost	$1050	$1050
Conversion-Device Cost	$100	$100
Expendables Cost	$185	$185
Conversion-Device Cost / Power Output	$50 / w	$50 / w
Expendables Cost/Work Output	$46/w yr	$46/w yr
Heat-Source Temperature	510 R	283 K
Heat-Sink Temperature	510 R	283 K
Carnot Efficiency	NA %	NA %
Overall Efficiency	35 %	35 %
Voltage Output of Conversion Device	28 vdc	28 vdc
Current Output of Conversion Device	0.072 amp	0.072 amp
Weight of Stored Ammonia	4100 lbm	1860 kg
Weight of Stored Water	6100 lbm	2770 kg

TABLE E-1

CHARACTERISTICS OF LIQUEFIED GAS EXPANSION SYSTEM

VALUE OF PARAMETER

Service: 5 watts for 2 yrs

PARAMETER	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	29,200 lbm	13,200 kg
Conversion-Device Weight	10 lbm	4 kg
Expendables Weight	25,600 lbm	11,600 kg
Buoyancy Force	17,800 lbf	8,100 kg
Conversion-Device Weight / Power Output	2 lbm/w	1 kg/w
Expendable Weight / Work Output	2550 lbm/w yr	1160 kg/w yr
Total System Displacement Volume	735 cu ft	21 cu m
Conversion-Device Volume	1 cu ft	0.028 cu m
Expendables Volume	734 cu ft	21 cu m
Conversion-Device Volume / Power Output	0.2 cu ft/w	0.0057 cu m/w
Expendables Volume	73.3 cu ft/w yr	2.1 cu m/w yr
Total System Cost	$2750	$2750
Conversion-Device Cost	$100	$100
Expendables Cost	$460	$460
Conversion-Device Cost / Power Output	$20/w	$20/w
Expendables Cost/Work Output	$46/w yr	$46/w yr
Heat-Source Temperature	510 R	283 K
Heat-Sink Temperature	510 R	283 K
Carnot Efficiency	NA %	NA %
Overall Efficiency	35 %	35 %
Voltage Output of Conversion Device	28 vdc	28 vdc
Current Output of Conversion Device	0.18 amp	0.18 amp
Weight of Stored Ammonia	10,200 lbm	4640 kg
Weight of Stored Water	15,400 lbm	7000 kg

Discussion of System

The liquefied gas expansion system is based on off-the-shelf hardware and knowledge. For low power, long life applications of the type sought in this study, excellent reliability and potentially rapid development are attributes possessed by this system.

There is a wide variety of liquefied gases which might be used. The studies conducted to date have included consideration of only two gases, ammonia and carbon dioxide; both are readily available at low cost and are supported by highly developed technologies. It is possible that the use of other fluids could result in systems that are superior to those reported here.

Included in the analysis is a calculation of the thermodynamic availability of a compressed or liquefied gas. The maximum possible useful work that can be obtained from a given quantity of gas is equal to the decrease in the availability of the gas for the process in question. It is impossible to derive, by any means, more than this quantity of useful work from the given quantity of gas. For example, the maximum useful work and the work from an isentropic expansion obtainable in expanding saturated liquid at 50°F to vapor at a pressure of 16 psia and a temperature of 50°F is as follows for the gases considered:

	Decrease in Availability	Isentropic Enthalpy Change
CO_2	78 Btu/lbm	50 Btu/lbm
NH_3	99 Btu/lbm	84 Btu/lbm

Note that the work from an isentropic expansion is less than the decrease in availability, illustrating how the availability change represents an upper limit on performance. Thus one can compute very quickly that to

Discussion of System

The liquefied gas expansion system is based on off-the-shelf hardware and knowledge. For low power, long life applications of the type sought in this study, excellent reliability and potentially rapid development are attributes possessed by this system.

There is a wide variety of liquefied gases which might be used. The studies conducted to date have included consideration of only two gases, ammonia and carbon dioxide; both are readily available at low cost and are supported by highly developed technologies. It is possible that the use of other fluids could result in systems that are superior to those reported here.

Included in the analysis is a calculation of the thermodynamic availability of a compressed or liquefied gas. The maximum possible useful work that can be obtained from a given quantity of gas is equal to the decrease in the availability of the gas for the process in question. It is impossible to derive, by any means, more than this quantity of useful work from the given quantity of gas. For example, the maximum useful work and the work from an isentropic expansion obtainable in expanding saturated liquid at $50^{o}F$ to vapor at a pressure of 16 psia and a temperature of $50^{o}F$ is as follows for the gases considered:

	Decrease in Availability	Isentropic Enthalpy Change
CO_2	78 Btu/lbm	50 Btu/lbm
NH_3	99 Btu/lbm	84 Btu/lbm

Note that the work from an isentropic expansion is less than the decrease in availability, illustrating how the availability change represents an upper limit on performance. Thus one can compute very quickly that to produce 35 KwHr at 35 per cent conversion efficiency (100 KwHr or 340,000 Btu) requires not less than 2400 lbs of liquid NH_3. This conclusion is valid regardless of the type of device used: i.e., Cartesian diver, underwater glider, expansion engine, etc. If the useful work is derived as a consequence of expanding liquefied gas, the minimum quantity of gas required is determined by thermodynamic laws.

It was generally found that the use of concrete storage tanks resulted in considerably less expensive but slightly heavier systems than those using steel tanks. It appears worthwhile to explore in some detail the possibility of using concrete for storage vessels.

Calculation Methods for System

The liquefied gas expansion system would use ammonia which is stored and boiled at a temperature of 50 F. The saturation pressure of ammonia at 50 F is 89 psia. Saturated ammonia vapor would enter the expansion engine and be expanded to about 16 psia. If this expansion were isentropic (adiabatic and reversible) which is the best possible process for this type of expansion engine, the change in enthalpy and therefore the maximum possible output would be 84 Btu/lbm of ammonia.

The overall efficiency for generating electric power was assumed to be 35 per cent of the energy available from a lossless system. Preliminary investigations indicate that expansion engines of the size required having 70 per cent efficiency are feasible. A generator efficiency of 50 per cent was assumed. It is contemplated that the engine and generator would be designed as a unit, sharing bearings, so that friction losses would be minimized. Thus the overall efficiency of this system is 35 per cent based on the isentropic expansion of the gas from the inlet pressure to the exhaust pressure. The electrical energy actually derived from the ammonia is about 29 Btu/lbm. The ammonia requirement can thus be calculated directly.

It has been assumed that thermodynamic equilibrium obtains in the water tank between the vapors and the absorbing medium, and that the temperature in the sink tank is the same as that of the ocean: thus the pressure in the water tank is determined by the composition of the material in the tank; i.e., the quantity of exhaust vapor that has entered. The mass of water to be used was determfined by the requirement that the pressure in the water tank just equals the design exhaust pressure when the last liquefied gas is consumed.

Two structural materials were considered for the storage vessels, namely steel and concrete. The steel is a low-carbon variety, and the concrete is reenforced and of the high-early-strength variety. For making estimates concrete was assumed to have a working stress in compression of 3000 psi and a density of 150 lbm per cu ft.

At the operating depth of 200 ft the ammonia storage vessel has negligible stresses, and the water tank is under compressive stress.

To alleviate stress problems and hence obtain light and inexpensive systems, it has been assumed that the tanks are carried to the launching site empty, and filled there with fluid at a temperature sufficiently low so that the saturation pressure of the liquefied gas is initially equal to atmospheric pressure. The liquefied gas would be transported in refrigerated containers, and would be loaded into the storage vessels just prior to lowering the power system into the ocean. The power system wo ld not be activated until the temperature of the fluid reached ocean temperature. The above procedure makes possible the use of very light tanks, for the loadings expected during shipment of full storage vessels are much in excess of those expected for the submerged vessels.

The cost of ammonia is $90 per ton, and water is presumed to be free. The cost of concrete, if used, is $40 per ton as cast in simple shapes. The engine-generator combination would cost about $100 in mass production. This cost of $100 for the combination is divided about equally between the engine and the generator. The pressure regulator to control the engine exhaust pressure would cost only a few dollars.

PROPANE-OXYGEN INTERNAL COMBUSTION ENGINE SYSTEM

Principle of Operation

The propane-oxygen internal combustion engine system burns propane and oxygen in a 4 stroke-cycle internal combustion engine. The engine drives a generator to produce electrical power. Because a reasonably efficient engine operating at a 2 watt or 5 watt output has not been produced, and is not considered feasible, a larger engine is used periodically to charge a nickel-cadmium battery. The battery is used as a continuous power supply for the load.

System Description and Operation

Figure F-1 illustrates the propane-oxygen internal combustion engine system. In terms of the energy conversion matrix of Fig. 1, the process is described as follows:

$$\text{Chemical Energy} \longrightarrow \underbrace{\underset{\text{Combustion}}{29a} \longrightarrow \text{Thermal Energy} \longrightarrow \underset{\text{Expansion}}{19a}}_{\text{Engine}} \longrightarrow \text{Mechanical Energy} \longrightarrow \underset{\text{Generator}}{45a} \longrightarrow \text{Electrical Enery} \longrightarrow \underbrace{\underset{\text{Charge}}{7a} \longrightarrow \text{Chemical Energy} \longrightarrow \underset{\text{Discharge}}{43b}}_{\text{Battery}} \longrightarrow \text{Electrical Energy}$$

In this closed engine-generator system, liquid propane, and oxygen stored initially at 6000 psia are metered to an internal combustion engine through suitable pressure regulators. The exhaust gases leaving the engine will be carbon dioxide and water, principally. A fraction of the exhaust gases will be recycled into the inlet of the engine to decrease the maximum cycle temperatures. The nitrogen present in air performs this same function of limiting maximum cycle temperatures for ordinary, land-based internal combustion engines. The remainder of the exhaust gases are passed through a calcium oxide bed where the gaseous carbon dioxide and water combine with the solid calcium oxide to form solid calcium carbonate and solid calcium hydroxide. A small fraction of the exhaust

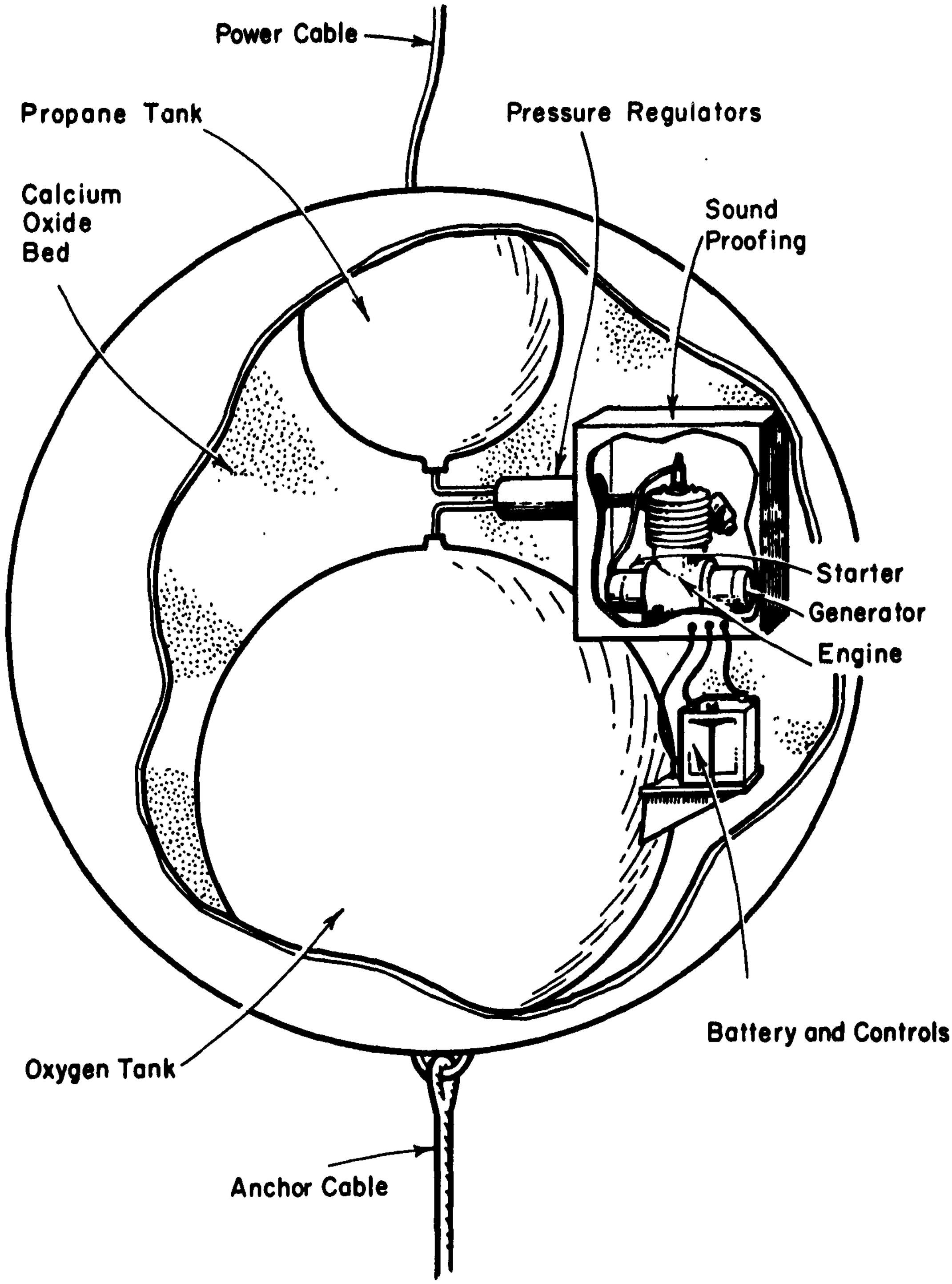

FIG. F-1 PROPANE-OXYGEN INTERNAL COMBUSTION ENGINE SYSTEM gases, two to four percent by mass, are compounds which will not be absorbed by the calcium oxide. These non-absorbed gases will cause the pressure in the encapsulating sphere to rise approximately 2 to 3 atmospheres over the course of the 2 year operating period. An increase in pressure of this magnitude will not significantly affect the operation of a four stroke-cycle engine.

The calcium oxide bed has ten per cent excess calcium oxide and is packed with a density equal to 100 pounds per cubic foot.

The closed system is based upon the following chemical reactions:

$$C_3H_{8(g)} + 5\,O_{2(g)} \longrightarrow 3\,CO_{2(g)} + 4\,H_2O_{(g)} + 20{,}000 \text{ BTU}$$

1 lbm   3.64 lbm   3 lbm   1.64 lbm

$$CO_{2(g)} + CaO_{(s)} \longrightarrow CaCO_{3(s)}$$

3 lbm   3.80 lbm   6.80 lbm

$$H_2O_{(g)} + CaO_{(s)} \longrightarrow Ca(OH)_{2(s)}$$

1.64 lbm   5.10 lbm   6.74 lbm

The sizes of batteries for the 2 watt and 5 watt systems are sufficiently large to permit charging once a day. In a typical system, the engine-generator would charge the battery for 30 minutes every 24 hours.

The entire system, including fuel-storage tanks, engine, generator, starter, controls, pressure regulator, sound suppressing material, battery, and calcium oxide bed are contained within a single encapsulation sphere.

The overall system characteristics are given in Table F-1.

TABLE F-1

CHARACTERISTICS OF CLOSED PROPANE-OXYGEN INTERNAL COMBUSTION ENGINE SYSTEM

VALUE OF PARAMETER

Service: 2 watts for 2 yrs

PARAMETER	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	2470 lbm	1120 kg
Conversion-Device Weight	22 lbm	10 kg
Expendables Weight	1155 lbm	525 kg
Buoyancy Force	100 lbf	45 kg
Conversion-Device Weight / Power Output	11 lbm/w	5 kg/w
Expendable Weight / Work Output	290 lbm / w yr	130 kg / w yr
Total System Displacement Volume	40 cu ft	1.17 cu m
Conversion-Device Volume	0.4 cu ft	.012 cu m
Expendables Volume	20 cu ft	.57 cu m
Conversion-Device Volume / Power Output	0.2 cu ft / w	.006 cu m / w
Expendables Volume / Work Output	5 cu ft / w yr	.14 cu m / w yr
Total System Cost	$765	$765
Conversion-Device Cost	$106	$106
Expendables Cost	$41	$41
Conversion-Device Cost / Power Output	$53 / w	$53 / w
Expendables Cost/Work Output	$10.2/w yr	$10.2/w yr
Heat-Source Temperature	NA R	NA K
Heat-Sink Temperature	NA R	NA K
Carnot Efficiency	NA %	NA %
Overall Efficiency	7.5 %	7.5 %
Voltage Output of Conversion Device	28 vdc	28 vdc
Current Output of Conversion Device	.07 amp	.07 amp

TABLE F-1

CHARACTERISTICS OF CLOSED PROPANE-OXYGEN INTERNAL COMBUSTION ENGINE SYSTEM

VALUE OF PARAMETER

Service: 5 watts for 2 yrs

PARAMETER	English Units	Metric Units
Operating Depth	200 ft	61 meters
Total System Weight	5700 lbm	2580 kg
Conversion-Device Weight	35 lbm	16 kg
Expendables Weight	2930 lbm	1330 kg
Buoyancy Force	700 lbf	318 kg
Conversion-Device Weight / Power Output	7 lbm/w	3 kg/w
Expendable Weight / Work Output	290 lbm / w yr	130 kg / w yr
Total System Displacement Volume	100 cu ft	2.83 cu m
Conversion-Device Volume	0.5 cu ft	.014 cu m
Expendables Volume	50 cu ft	1.42 cu m
Conversion-Device Volume / Power Output	.1 cu ft / w	.003 cu m / w
Expendables Volume / Work Output	.5 cu ft / w yr	.14 cu m / w yr
Total System Cost	$1575	$1575
Conversion-Device Cost	$130	$130
Expendables Cost	$103	$103
Conversion-Device Cost / Power Output	$26 / w	$26 / w
Expendables Cost/Work Output	$10.3/w yr	$10.3/w yr
Heat-Source Temperature	NA R	NA K
Heat-Sink Temperature	NA R	NA K
Carnot Efficiency	NA %	NA %
Overall Efficiency	7.5 %	7.5 %
Voltage Output of Conversion Device	28 vdc	28 vdc
Current Output of Conversion Device	.18 amp	.18 amp

Although the system described is closed, two open variations on this system have been considered. In one variation, the exhaust gases are vented to the ocean through a check valve. In a second variation, the system is located near or on the surface so that a snorkel or similar apparatus allows the engine to consume atmospheric air instead of stored oxygen, and to exhaust directly to the atmosphere. A summary of calculated results on the three systems is presented in Table F-2.

TABLE F-2

COMPARISON OF ENGINE-GENERATOR SYSTEMS FOR 2 WATTS FOR 2 YEARS*

System	Cost $	Weight lbs	Volume ft^3	Operating Depth, ft
Closed: exhaust gases absorbed in CaO bed	765	2470	40	200
Open Exhaust: exhaust gases vented overboard	745	1500	32	100
Air Breathing: air is a combustant, exhaust gases vented overboard	195	240	6	Near or on surface

*The corresponding cost figures for the systems to produce 5 watts for 2 years vary more widely. The closed system costs $1580, the open exhaust system costs $1540, and the air breathing system costs $245.

Discussion of System

A wealth of experience exists in the internal combustion engine field. Highly reliable, small, long life engines have been developed (F-1) for many portable power needs. We conclude that a highly reliable engine-generator system can be made which will satisfy all of the requirements specified herein.

If it is possible to locate an air breathing system on or near the surface, a several-fold reduction in the cost of an engine-generator system can be achieved. However, it appears that an open exhaust system offers little cost advantage over the closed system.

A possible development problem of the internal combustion engine system may be its noise. However, sound suppressing techniques probably can keep the engine noise level low and comparatively isolated. The acceptability of the noise level would have to be determined by test.

Calculation Methods for System

The efficiencies of the various individual processes in the internal combustion engine system are given as follows:

Chemical-to-mechanical conversion efficiency = 20%

Mechanical-to-electrical conversion efficiency = 50%

Electrical-to-storage-to-load transfer efficiency = 75%

This combination of efficiencies of individual processes result in the following overall conversion efficiency:

Overall conversion efficiency = 7.5%

The system output of 2 watts for 2 years is equivalent to 119,500 Btu of electricity. Thus, at an overall conversion efficiency of 7.5%, 1,600,000 Btu of heat are required. The quantities of fuel and oxidant needed to produce the required amount of heat are 80 lbm of propane and 290 lbm of oxygen since the heating value of the reaction is approximately 20,000 Btu/lbm of propane.

The costs, weights, and dimensions of the engine with starter and soundproofing are unique, in this study, to the internal combustion engine system. The estimates on these components given herein are based on the costs, weights, and dimensions of similar equipment. The cost of propane was estimated to be 5 cents per pound. The cost of calcium oxide is $20 per ton. Cost, size, and weight of the battery are based on figures contained in the sections on batteries in this report. The remainder of the estimates were made in accordance with the section entitled, "Assumptions Used in System Analyses." A detailed list of costs, weights, and volumes is given in Table F-3.

TABLE F-3

DETAILED ESTIMATES OF COSTS, WEIGHTS, AND VOLUMES OF COMPONENTS OF PROPANE-OXYGEN INTERNAL COMBUSTION ENGINE SYSTEM

A. 2 watts for 2 years

Item	Cost ($)	Wt (lbm)	Vol. (cu ft)
Propane	4	80	2.2
Oxygen	29	290	9.7
Calcium Oxide	8	785	7.85
Propane Tank (net)	10	40	.1
Oxygen Tank (net)	422	844	1.74
Engine with Starter	40	12	.25
Generator	50	1	--
Battery	16	9	.1
Sound Proofing	25	5	2
Pressure Regulators	50	5	--
Miscellaneous	25	10	.5
Container (Diameter = 4.3 ft)	86	285	40
	765	2366	

B. 5 watts for 2 years

Item	Cost ($)	Wt (lbm)	Vol. (cu ft)
Propane	10	200	5.5
Oxygen	73	730	24.0
Calcium Oxide	20	2000	20
Propane Tank (net)	25	100	.2
Oxygen Tank (net)	1060	2120	4.4
Engine with Starter	40	12	.25
Generator	50	1	--
Battery	40	22	.2
Sound Proofing	25	5	2
Pressure Regulators	50	5	--
Miscellaneous	25	10	.5
Container (Diameter = 5.9 ft)	159	530	100
	1577	5735	